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## Micro-generation for UK Households: Thermodynamic and Related Analysis

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# **MICRO-GENERATION FOR UK HOUSEHOLDS**

## **THERMODYNAMIC AND RELATED ANALYSES**

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath  
Department of Mechanical Engineering  
June 2009

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# ABSTRACT

Micro-generation is the small-scale and localised provision of heat or electricity. Micro-generators have the potential to reduce greenhouse-gas emissions and enhance energy security by providing heat or electricity from either renewable sources, or via the more efficient use of fossil fuels. But this potential is often unquantified or unclear, and hence quantitative information is required concerning both the energetic performance of micro-generators and their ability to provide net reductions in carbon emissions.

In the context of household energy provision in the UK, thermodynamic and related carbon analyses of three micro-generation technologies have been carried out. These studies contribute to the research of the SUPERGEN 'Highly Distributed Power Systems' Consortium, which has been addressing a broad range of issues regarding micro-generation. The technologies analysed here are a grid-tied micro-wind turbine (rotor diameter 1.7m, rated power 600 W at 12 m/s), a grid-tied solar photovoltaic array (15 m<sup>2</sup>, 2.1 kW<sub>p</sub> mono-crystalline silicon), and a solar hot-water system (2.8 m<sup>2</sup> flat-plate collector, direct-feed system). Annual energy outputs were estimated and contextualised against the demands of representative UK households. The overall energy-resource and carbon savings provided by the micro-generators were assessed on the basis that they (partially) displace the established supply systems. Savings were then compared with the energy-resource and carbon 'debts' of the micro-generators to determine their net performance.

The displaced energy or carbon payback periods of the micro-generators were estimated to be well within their estimated lifetimes: a maximum 2.5 years for the SHW system, 3.1 years for the micro-wind turbine installed in an 'open' environment, and 7.4 years for the solar PV system. After payback, net energy-resource and carbon savings accrue. This thesis thus demonstrates that, given appropriate UK installations, all three micro-generators can reduce carbon emissions and enhance energy security by reducing use of, and dependence upon, fossil fuels.





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# GLOSSARY

<b>AC</b>	Alternating current.
<b>Ambient energy</b>	Natural energy flows such as solar, wind, and wave energy (Patterson 2007b).
<b>BERR</b>	The UK's 'Department for Business, Enterprise and Regulatory Reform'; formerly the 'DTI' (see below).
<b>BRE</b>	Building Research Establishment.
<b>BWEA</b>	British Wind Energy Association.
<b>CEGB</b>	Central Electricity Generating Board.
<b>DC</b>	Direct current.
<b>Delivered energy</b>	Commercial energy carriers (e.g. fuel or electricity) delivered to the end-user (see Appendix B; p.213).
<b>DTI</b>	The UK's 'Department of Trade and Industry', now 'BERR' (see above).
<b>EC</b>	European Commission.
<b>Embodied carbon</b>	The total (direct and indirect) carbon-dioxide equivalent emissions associated with a product or activity at the point of either production or delivery to the end-user.
<b>Embodied energy</b>	The total (direct and indirect) energy requirement a product or activity at the point of either production or delivery to the end-user. Energy requirements are traced back to their naturally occurring form and quantified in terms of enthalpy.
<b>Energy carrier</b>	A material or phenomenon that can store energy or transport it from place to place, usually by implication under human control; all fuels plus electricity (Patterson 2007b).
<b>Energy requirement for energy (ERE)</b>	The gross energy requirement of an energy carrier, per unit of that energy carrier (see Section 2.3.7.3; p.20).
<b>Energy resource</b>	Defined in Section 2.3.3 (p.13).
<b>Energy service</b>	What the end-user actually wants: a room at a desired temperature; transportation over a certain distance; the manufacture of a product from raw materials; and so on (see Appendix B; p.213).

<b>Enthalpy</b>	A thermodynamic property that equals the sum of a fluid's <i>internal energy</i> and its <i>pressure</i> multiplied by its <i>volume</i> (Rogers and Mayhew 1992).
<b>Enthalpy of combustion</b>	The difference between the enthalpy of the products of combustion and the enthalpy of the reactants, each on a per mole of fuel basis, when complete combustion occurs and both reactants and products are at the same temperature and pressure (Bejan et al. 1996 p.79). The magnitude of the enthalpy of combustion is referred to as the 'calorific value', and two forms are recognised: the gross calorific value (GCV) and the net calorific value (NCV). The GCV is obtained when all the water formed by combustion is a liquid; the NCV is obtained when all the water formed by combustion is a vapour.
<b>EPSRC</b>	Engineering and Physical Sciences Research Council.
<b>Exergy</b>	The maximum amount of work obtainable from a thermodynamic system when it is brought into equilibrium with its environment via reversible interactions with that environment only (definition based upon Kotas 1985, Bejan et al. 1996, and Dewulf et al. 2008).
<b>Fuel</b>	'Material for a fireplace' – matter that is utilised to produce heat (Patterson 2007b).
<b>Fuel oil</b>	The heavy oils from the refining process; used as fuel in furnaces and boilers of power stations, industry, in domestic and industrial heating, ships, locomotives, metallurgic operations, and industrial power plants etc.
<b>Full insulation</b>	'At least 100mm of loft insulation where a loft is present; cavity wall insulation where there is a cavity; and at least 80% of windows being double-glazed' (Utleay and Shorrocks 2008).
<b>GCV</b>	Gross calorific value, also referred to in the literature as 'higher heating value' (HHV). See 'enthalpy of combustion'.
<b>GHG</b>	Greenhouse gas, measured in 'carbon-dioxide equivalent' terms.
<b>Gross energy requirement (GER)</b>	The sum of all the energy resources that had to be sequestered in order to produce the product or service. Here 'sequestered' is used in the sense of 'set apart', to indicate that energy may be 'tied up' in the finished product in addition to the energy used during production (see Section 2.3.2; p.213).
<b>HAWT</b>	Horizontal-axis wind turbine.
<b>Heat engine</b>	An engine that converts heat input into work output via a cyclic process.

<b>Irreversible process</b>	See ‘reversible process’.
<b>Met Office</b>	Originally an abbreviation for ‘Meteorological Office’, but now the official name of the UK’s national weather service.
<b>Micro-generation</b>	Insert my definition. But note that ‘generation’ implies electricity. We ‘generate’ electricity, but strictly we don’t ‘generate’ anything – we convert one form of energy into another.
<b>MTP</b>	DEFRA’s ‘Market Transformation Programme’.
<b>NCV</b>	Net calorific value, also referred to in the literature as ‘lower heating value’ (LHV). See ‘enthalpy of combustion’.
<b>Net energy requirement (NER)</b>	The net energy requirement is the gross energy requirement minus any energy still available in the product of interest (see Section 2.3.4; p.15).
<b>Primary energy</b>	Energy that is ‘drawn (extracted or captured) from natural reserves or flows’. This term is, however, inconsistently used - see Appendix B and Section 2.3.3 (pages 213 and 13 respectively).
<b>Reversible process</b>	A process is reversible if it is possible to return to its initial conditions, and irreversible otherwise. For further discussion, see Kotas 1985 pp.12–17, 71–72 or Bejan et al. 1996 pp.46–48.
<b>SEDBUK</b>	Seasonal Efficiency of Boilers in the UK.
<b>VAWT</b>	Vertical-axis wind turbine.



# CHAPTER 1

## INTRODUCTION

### 1.1 BACKGROUND

Energy is a fundamental part of human life, providing comfort, light, communication, transportation, and many more services to people all over the world. Most current methods of energy use, however, entail resource uncertainties and environmental impacts on a local, regional and global scale (Hammond 2004a). The use of fossil fuels is a prominent example. Fossil fuels are the main energy source used across the world (IEA 2008), but the security of their continued supply is uncertain for many nations and most scientific evidence suggests that, among other impacts, their use is contributing to climate change (DTI 2007b; IPCC 2007). Energy use in the UK is based overwhelmingly on fossil fuels (BERR 2008a) and accounts for over 97% of emissions of carbon dioxide, the main greenhouse gas (DEFRA 2008a). Alongside the negative environmental impacts associated with this situation there are significant concerns about energy security, as the UK is an increasing net importer of fossil fuels (DTI 2007b). Since the UK Government's energy policy aims are to cut greenhouse-gas emissions by at least 80% from 1990 levels by 2050, and to maintain secure, diverse supplies of energy (DECC 2009), significant changes are required in the way that energy is sourced and used.

### 1.2 MICRO-GENERATION AND THE UK'S RESIDENTIAL SECTOR

The UK's residential sector consists of 26 million households that account for approximately one-third of delivered-energy use and carbon-dioxide equivalent ( $\text{CO}_{2\text{eq}}$ ) emissions (BERR 2008e; DEFRA 2007). There is a large potential for improvements in the way energy is used within this sector. These improvements underpin a variety of studies that indicate that significant reductions in carbon emissions are technically feasible (e.g. Johnston et al. 2005; Shorrock et al. 2005; Boardman et al. 2005; Natarajan and Levermore 2007; Boardman 2007). While differing analyses have different emphases, some common threads emerge that unite their general message. On the demand side, the infrastructure and end-use technologies of the housing stock can be substantially improved to enable the provision of energy services with far less delivered energy. On the supply side, the studies indicate that the energy supplied to UK households can be much cleaner and less carbon intense than at present, and that micro-generators of various forms have a role to play in achieving this.

*Micro-generation* is defined in Section 82 of the UK's Energy Act (2004) as the production of electricity or heat from a low-carbon source at capacities of no more than 50  $\text{kW}_e$  or 45  $\text{kW}_{\text{th}}$ . It embraces a variety of technologies, including micro-wind turbines, solar photovoltaic arrays, solar hot-water systems, combined heat-and-power units and heat pumps. These technologies were summarised during earlier research that underlies this thesis and has been published by Allen et al. (2008c), which is reproduced in Appendix E.



(The present author was corresponding and lead author of that paper, and presented an earlier version of the work at the '3rd International Green Energy Conference', Mälardalen University, Västerås, Sweden; 18-20 June 2007.) Micro-generators have the potential to reduce carbon emissions and enhance energy security through either more efficient use of fossil fuels, or by providing heat or electricity from ambient, renewable energy flows such as solar or wind energy. Recent estimates by Element Energy (2008a) indicate that micro-generators are installed on only 0.4% of UK households (approximately 110,000 installations compared to 26 million households), although several sources suggest that there is potential for their numbers to increase significantly during the next few decades (e.g. Energy Saving Trust et al. 2005; Burt et al. 2008).

There are, however, a range of technical, economic, regulatory and information-related barriers constraining the uptake of micro-generation (DTI and OFGEM 2007; Allen et al. 2008c). Furthermore, and crucially, the performance of some emergent micro-generation options is currently uncertain. For the adoption of micro-generators to be both appropriate and effective, it is vital that quantitative information is produced regarding the energetic performance of micro-generators and their ability to reduce both the use of fossil fuels and carbon emissions. This research aims to contribute such information to the literature.

### 1.3 THERMODYNAMICS AND ENERGY SYSTEMS

The focus of this thesis is the use of thermodynamic concepts to analyse the energetic performance of micro-generators for UK households. Since current patterns of energy use are closely related to carbon emissions, the latter being the subject of challenging reduction targets, this thesis also investigates the effect micro-generators could have on carbon-dioxide emissions.

As a science of energy, thermodynamics can aid the understanding and analysis of energy-supply systems and technologies. By physically quantifying energy flows, it can identify losses and the potential for improvement within an energy system, and thus provide information to enable more effective and sustainable energy use. But energy systems are, of course, much more than just flows of energy. They are complex entities that involve a plethora of technical, economic, environmental and other interactions, the majority of which are far beyond the scope of thermodynamic considerations. This indicates that while thermodynamic analysis can provide a useful contribution to an energy-systems assessment, it should not do so alone.

The need for an interdisciplinary perspective in a move towards more sustainable energy use is reflected in the concept of *sustainable development*, which may be defined as the process by which *sustainability* (the capacity for continuance) is achieved (Parkin 2000). The concept came to prominence with the publication of *Our Common Future* in 1987, which recognised that the traditionally separate concerns of the environment, the economy and social issues are increasingly interrelated and should thus be treated as one (World Commission of Environment and Development 1987). This suggests that an energy-systems assessment should draw insights from a variety of disciplines in an integrated and cohesive manner.

## 1.4 AIMS AND OBJECTIVES

In order to contribute to a performance assessment of micro-generation options for the UK's residential sector, and in accordance with the need for an interdisciplinary approach to such assessment, the primary aims of this research are:

- Aim 1.** To assess the thermodynamic and related carbon performance of a selection of micro-generation technologies in the context of residential energy provision in the UK.
- Aim 2.** To contribute to the development of an interdisciplinary 'integrated appraisal' methodology for sustainability assessment, with application to the selected micro-generators. This methodology includes two elements other than thermodynamic analysis – environmental life cycle assessment (LCA) and economic cost-benefit analysis (CBA).

The two aims of this research are in fact inter-linked; the thermodynamic analyses provide data to the other elements of the integrated appraisal, and vice versa. These inter-linkages are discussed in further detail in Section 2.6. A range of objectives have been defined to achieve the aims specified above:

- Obj. 1.** To outline relevant fundamental concepts of thermodynamics (Chapter 2).
- Obj. 2.** To synthesise and describe energy and carbon data for the established methods of energy supply in the UK, in order to enable an assessment of the relative performance of the micro-generators (Chapter 3).
- Obj. 3.** To synthesise and analyse data regarding the use of energy within the residential sector of the UK, to give context to the performance of the micro-generators (Chapter 4).
- Obj. 4.** To analyse the thermodynamic and related carbon performance of a selection of micro-generators (Chapters 5 and 6). The selected micro-generators are a micro-wind turbine, a solar photovoltaic array, and a solar hot-water system – each defined in detail during their respective analyses. The analyses have four elements:
  - a.** To estimate the annual energy/exergy outputs of the selected micro-generators;
  - b.** To give context to these outputs by comparing them with representative household energy demands from Chapter 4;
  - c.** To estimate the annual energy-resource and carbon-emission savings enabled by the micro-generators, by considering that the latter reduces the use of the established supply systems analysed in Chapter 3;
  - d.** To estimate the net energy and carbon performance of the selected micro-generators, i.e. to determine whether or not the energy and carbon saved by the micro-generators is greater than that 'invested' within them.
- Obj. 5.** To incorporate the analyses with the other 'integrated appraisal' methods in order to provide an interdisciplinary assessment of the micro-generators.
- Obj. 6.** To discuss the advantages and disadvantages of the thermodynamic analysis techniques, in the context of the micro-generator assessments (Chapters 7 and 8).

This thesis constitutes a variety of separate but inter-linked studies, and it is essential that these are discussed coherently and with respect to one another. Consequently, key points are summarised within chapters, but a discussion of the findings of each chapter is presented as one overall discussion in Chapter 7. Conclusions and recommendations for further work then follow in Chapter 8.

The author's collaborative work has been published, to date, by Allen et al. (2008a, 2008b and 2008c; all reproduced in Appendix E). The integrated appraisal has, in turn, been part of a wider collaborative research initiative involving universities and industrial partners from across the UK. This initiative, the EPSRC<sup>1</sup>-led SUPERGEN 'Highly Distributed Power Systems' Consortium, has been addressing some of the challenges associated with a move toward more distributed energy supply systems. Some recent publications of this consortium (including Allen et al. 2008b) were brought together in a special issue of proceedings of the UK's Institution of Mechanical Engineers (see Burt et al. 2008).

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<sup>1</sup> 'EPSRC' – Engineering and Physical Sciences Research Council

## CHAPTER 2

# AN INTRODUCTION TO THERMODYNAMIC ANALYSIS TECHNIQUES

*'The First Law says there is no such thing as a free meal, and the Second Law says you can't break even, anyway.'* Anon, in Slessor (1978).

### 2.1 INTRODUCTION

Thermodynamics is a branch of science that quantifies energy flows and conversions in physical terms. As such, it can aid the design, analysis and optimisation of energy systems and their component parts. The foundations of modern thermodynamic analysis techniques were laid in the 19<sup>th</sup> century, but it was not until the latter half of the 20<sup>th</sup> century that the analysis methods used within this thesis emerged. These techniques are *energy analysis* and *exergy analysis*, and they are introduced within this chapter following an introduction of some fundamental thermodynamic concepts. Energy and exergy analysis can provide complementary quantification of energy flows, and the ways in which the methods used later in this thesis are defined within this chapter.

### 2.2 FUNDAMENTAL CONCEPTS

#### 2.2.1 Energy transfers and enthalpy

Energy can be transferred into and out of a system via *mass*, *heat*, or *work* interactions (Bejan et al. 1996). The First Law of Thermodynamics states that while energy can be transferred between systems, or converted from one form to another, the total amount is always conserved (*ibid*). From this key concept emanates the idea of an *energy balance* applied around a defined system boundary – for a closed or steady-state open system the sum of the outputs equals the sum of the inputs.

The objective of many engineering plant is to enable energy transfer via heat or work, in many cases with the ultimate objective of converting one form of energy into another (Rogers and Mayhew 1992). Through application of the First Law it is possible to calculate the quantities of heat and work that cross the boundary of a system when a given change in (thermodynamic) properties occurs (*ibid*). Within a steam power plant, for example, the boundary may be drawn around the boiler, and the First Law used to calculate the heat required to generate steam at a given pressure. Similarly, the boundary can be drawn around the turbine in order to calculate the work done as the steam expands through that turbine (*ibid*). The property *enthalpy* is useful for these purposes, which equals the sum of a fluid's *internal energy* (a function of temperature) and its *pressure* multiplied by its *volume*. The enthalpy change within the boiler is proportional to the heat input to the boiler, while

the enthalpy change across the turbine is proportional to the work output of that turbine (*ibid*).

In many cases, such as the case of a power plant, an analyst is concerned with how much heat, normally supplied by burning a fuel, can be converted into work by a *heat engine* (Rogers and Mayhew 1992). The First Law implies that all heat can be converted into work, since it treats these energy transfers as equivalent. But the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted into heat (via dissipative processes), not all heat input can be converted into useful work (Hammond 2004a). This is an important distinction that is worth considering in more detail.

Carnot's theorem, which was subsequently given rigorous proofs by Kelvin and later Clausius, states that the maximum amount of work that can be derived from a heat source depends upon the temperature of that source,  $T$ , and the temperature of the heat sink,  $T_0$  (Slessor 1978). This can be expressed as the 'Carnot efficiency':

$$\eta_{Carnot} = 100 \times \left( \frac{T - T_0}{T} \right) = 100 \times \left( 1 - \frac{T_0}{T} \right) \quad 2-1$$

This is the maximum efficiency attainable when converting heat into work via ideal (reversible) processes. During coal-fired electricity generation, for example, coal is burnt to raise steam at high pressure, which then expands through a turbine (or turbines) to generate electricity. A representative value for steam temperature at turbine entry is 723 K (450 °C) and at exit, prior to condensation, 333 K (60 °C). These values were taken from Slessor (1978), which is valid since the majority of coal-fired stations operating in the UK in 2007 were built in the late 1960s and early 1970s (BERR 2008a). Equation 2-1 indicates that the maximum quantity of work that could be extracted is 54% of the heat initially transferred to the steam by the boiler; the rest being subsequently emitted during condensation and thus wasted. In fact much less work is obtained, because the Carnot efficiency is for an ideal, reversible process. In real-world processes, irreversibilities and both technical and economic constraints dictate reductions from the ideal. The average annual efficiency for all UK coal-fired power generation was approximately 36% during 2003–2007 (BERR 2008a). This efficiency is based on the Gross Calorific Value (GCV) of the fuel input. Nevertheless, the Carnot efficiency acts as a useful guide as to the scope for potential improvement. It is certainly more realistic than an aspiration of a 100% conversion efficiency from heat into work, which might be assumed on the basis of a First Law energy balance in isolation (outputs = inputs).

The Carnot efficiency is one postulate (of many) of the Second Law of Thermodynamics (Bejan et al. 1996). The Second Law indicates that, from the perspective of available work, a heat source is more useful the greater the temperature difference between itself and the heat sink. It also dictates that, although heat can flow down a temperature gradient unaided, shaft work or an electrical energy input is required in order

for heat transfer to take place from a cold to a hot reservoir, as in the case of a heat pump (Hammond 2004a).

### 2.2.2 Exergy

The implications of the foregoing – that different energy transfers have differing work potentials – is that it can be useful to describe the maximum amount of work available in an energy flow or system. This is encapsulated in the property *exergy*, which may be defined as *the maximum amount of work obtainable from a thermodynamic system when it is brought into equilibrium with its environment via reversible interactions with that environment only* (definition based upon Kotas 1985, Bejan et al. 1996, and Dewulf et al. 2008). The conceptual *environment* is an idealised form of the real environment and is characterised by a perfect state of equilibrium, which means an absence of any differences involving pressure, temperature, kinetic energy, potential energy, and chemical potential (Kotas et al. 1995). When a system is in physical (but not chemical) equilibrium with its environment, it is said to be in the *environmental state* (which is also known as the *restricted dead state*). When a system is also in chemical equilibrium with its environment, it is said to be in the *dead state* (Kotas et al. 1995; Bejan et al. 1996).

Like energy, exergy is transferred via mass, heat or work interactions. Exergy, however, can be destroyed and is generally not conserved (Bejan et al. 1996), and so when an *exergy balance* is applied around a system or subsystem, the exergy output will be less than the input and the associated *exergy efficiency* will be less than 100%. *Exergy destruction* is associated with irreversibilities within the system boundary of interest; a phenomenon that accompanies all real-world processes (Tsatsaronis 2007). *Exergy losses* occur across the system boundary when exergy is transferred across that boundary with material or energy streams. The terms ‘destruction’ and ‘loss’ appear to be used interchangeably in the literature, probably because exergy analysis has not been formally codified in the way that energy analysis was during 1974–75 (Section 2.3.2). When analysing an individual process or component, the distinction between destruction and loss appears useful, but when the boundary of interest is drawn more widely; around technologies as a whole or even around whole energy systems, all exergy degradation becomes ‘destruction’ within the system boundary.

Exergy destruction is a key concept. By identifying its locations, causes, and magnitudes within a system, useful insights may be drawn concerning the effectiveness of energy interactions (Bejan et al. 1996). For example, consider again electricity generation with a coal-fired power plant. Reistad (1975) presented a detailed breakdown of the energy and exergy losses (it is thought that the latter is in fact ‘destruction’ as defined here) across each component of a U.S. coal-fired power station, summarised in Table 2-1. Such power generation follows a *vapour power cycle*, using water as the working fluid (e.g. Rogers and Mayhew 1992). Table 2-1 indicates that though the overall energy and exergy efficiencies are similar, the breakdown of the energy and exergy losses is different. The majority of the total plant *energy* losses occur in the condenser: heat emission from the working fluid (quantifiable by considering the enthalpy change of that fluid). But because this heat emission is occurring at low temperature (close to the environmental temperature), the

Carnot efficiency indicates that the ‘work potential’ (Kotas 1985) of this process is very low, and hence the exergy change (loss) is very small during the process.

**Table 2-1: Thermodynamic performance of coal-fired power stations**

Plant components	Energy losses % of plant input	Exergy losses % of plant input
Steam generator	9.0	49.0
Combustion		(29.7)
Heat exchanger		(14.9)
Thermal stack loss		(0.6)
Diffusional stack loss		(3.8)
Turbines	~0	4.0
Condenser	47.0	1.5
Heaters	~0	1.0
Miscellaneous	3.0	5.5
Plant totals	59.0	61.0
Generation efficiencies*	$\eta = 100 - 59 = 41$	$\Psi = 100 - 61 = 39$

Source: Reistad (1975)

\* Efficiencies based on gross calorific value (higher heating value). The First Law energy efficiency is higher than those quoted above for UK coal-fired plant because of the higher operating temperatures typically adopted in US power plant practice (Hammond 2004a)

The foregoing indicates that an isolated First Law perspective would suggest that the condenser is a major source of thermodynamic inefficiency. Second Law insights, seen here via the concept of exergy, clearly indicate that in fact the condenser is relatively benign in exergy terms, and consequently the efficiency of electricity generation cannot be improved much via improvements in the condenser. Other components are responsible for much greater exergy destruction. Table 2-1 shows that the majority occurs during steam generation, during both combustion and heat transfer between the products of combustion and the working fluid. In both cases a large proportion of the destruction in these two process is unavoidable; it is intrinsic to the energy conversion process (Bejan et al. 1996 p.161, Kotas 1985 p.71) and hence cannot be reduced by improved technology. The concept of unavoidable exergy destruction will be revisited later in this chapter, but for now the pertinent point is that the concept of exergy is providing different and complementary insights to those of an isolated First Law assessment.

### 2.2.3 The system boundary

When assessing the performance of a process and looking for possible improvements, the scope of interest – the system boundary – has a key influence on the conclusions drawn. Individual process improvements will always face technical and economic constraints, but improvements may also be possible through a combination of different processes, as the following examples indicate. A broad scope – a wide system boundary – is required to identify such possibilities within an energy system of many supply options and many demand structures.

Equation 2-1 indicates that the work potential of a heat source depends upon the temperature difference between that source and the heat sink. Because thermal processes exhaust waste heat, and because different thermal processes have different temperature requirements, there is scope for the method of *heat cascading* from higher to lower

temperature processes (see, for example, van Gool 1987 or Hammond 2007b). When the waste heat output of one process is of sufficient temperature to drive a secondary process (and other conditions are also suitable), a greater energy efficiency can be achieved through their combination.

For example, a gas turbine operates at relatively high temperature generating electricity via a *gas power cycle* (based upon the *Joule cycle*), and the waste heat can be of sufficiently high temperature to form steam within a vapour power cycle (Rogers and Mayhew 1992). Thus, a 'combined cycle gas turbine' (CCGT) plant cascades heat from the gas power cycle to the vapour power cycle and an overall efficiency improvement is made compared to either process operating in isolation. The average electricity-generating efficiencies for operating CCGT plants in the UK were 49% (GCV) in 2007 (BERR 2008a), compared to 36% for isolated coal-fired plant, and have reached above 60% with modern plant – greater than either cycle operating in isolation (Çengel and Boles 2006).

In other cases, waste heat of low temperatures can be useful for certain heating applications. Buildings use large quantities of low-temperature heat ( $< 100\text{ }^{\circ}\text{C}$ ). In 2004, for example, approximately 61% of the fuel and electricity delivered to residential buildings was used for space heating (to provide average internal temperatures of  $20^{\circ}\text{C}$  or so; Shorrock and Utley 2003) and 23% was for water heating (at around  $50^{\circ}\text{C}$ ; Energy Saving Trust 2008). By generating electricity close to the demand, rather than within a large centralised plant such as the coal-fired power station previously discussed, some of the 'waste' heat may be used for heating purposes in a process referred to as *combined heat and power* (CHP) or *cogeneration*. The electrical efficiency is typically lower than optimised electricity-only generation processes, but the overall First Law efficiency can be increased due to the use of low-temperature heat, to as much as 80% in comparison to the 60% for the modern CCGT outlined above (Hammond 2004a). Given that the majority of the energy used in buildings such as homes is for low-temperature heating processes, this is an attractive proposition in energy terms. Transmission and distribution losses – which were approximately 7% of the electricity generated in the UK in 2005 (Section 3.4.5; p.50) – are also reduced by generating close to the load. Some countries use CHP extensively. Denmark and the Netherlands, for example, provided approximately 40% of total electricity generation via CHP over the period 2001–2003 (Euroheat & Power 2005). CHP does not, however, play a significant role yet in the UK, although the Government is attempting to increase its use, due to the potential fuel savings it offers, via a number of incentives (BERR 2008a). By 2007, only 7% of total electricity was generated via CHP (with an average, overall First Law efficiency of 66%), compared to over 70% emanating from conventional power plant and CCGT (BERR 2008a).



#### 2.2.4 Wider system boundaries

The principle of widening the system boundary when assessing the performance of energy technologies can be applied further still. All of the supply technologies mentioned thus far require energy inputs to be produced in the first place, to be maintained during their lifetime, and possibly to be decommissioned. From this perspective it might be seen that the technology is in fact a net energy ‘sink’ – if its energy requirements outweigh the energy it supplies to society. This concern led to the development of *net energy analysis*; a subject discussed in Section 2.3.7 (p.19).

The system boundary can also extend downstream of energy-supply technologies to consider the structure of the energy demand. This can have a crucial influence on the most appropriate quantity and mixture of supply technologies. If the majority of the demand is for lighting, for example, electricity generators may be most appropriate, but if the majority is for space or water heating, boilers or other direct heat-supply technologies might be preferable. If there are opportunities to reduce demand through, say, improved insulation, the optimal supply technologies to meet the remaining heat demand may change from the baseline situation. The spatial and temporal natures of energy demands can also affect the feasibility of different technology options. CHP, for example, may be less attractive if heat and electricity demands are not concurrent temporally and geographically, or if their relative proportions do not match the proportional outputs of the CHP plant.

The influence of energy demand on the relative performance of supply technologies suggests that ‘net energy analysis’ – the separation and analysis of an energy supply system from the end-uses of that energy – is not enough on its own. It will need to be complemented with analyses of energy demands in order to provide a thorough assessment of the potential for improvement within energy systems. This issue will be revisited in the net energy analysis section (Section 2.3.7, p.19).

#### 2.2.5 Sustainable energy systems and the role of thermodynamics

There are many other factors beyond thermodynamic issues that influence the development and operation of energy supply systems. Such systems involve complex socio-economic, political, and technical interactions, and have side-effects that include environmental risks on a local, regional and global scale. Examples of specific issues are: the availability and price of fuels and energy-technology options; the social acceptability of, and environmental impacts associated with, energy technology options; and, in the case of an electricity network, the electrical engineering implications of different generators and loads (e.g. power quality, network stability, and so on). Reconciliation of these conflicting factors is a complex matter that is difficult to resolve by formal methods. Rather than attempting to calculate an optimal solution, a pragmatic approach is required, what is often termed ‘satisficing’ in the management literature (Hammond 2000).

Nevertheless, the foregoing discussion implies that thermodynamics can make a useful contribution to the analysis and improvement of energy systems. Since current patterns of energy use are closely related to carbon emissions, the latter being the subject of

challenging nation-wide reduction targets, thermodynamic analyses can be utilised to assess the carbon-saving potential of proposed changes. This is done within this thesis during the analysis of micro-generation technologies. Thermodynamics can thus provide an 'evidence-based' means of analysing moves towards, and criteria for, sustainability (Hammond 2004a). Two available thermodynamic analysis techniques – energy analysis and exergy analysis – are used to varying extents within this thesis to assess the performance of a variety of micro-generators in the contexts of both residential energy provision and the established energy-supply system in the UK. The two techniques are now outlined and discussed, prior to their later application.

## 2.3 ENERGY ANALYSIS

### 2.3.1 Background

*Energy analysis* developed amongst increasing concern about resource depletion and scarcity before receiving an upsurge of interest as a result of the first oil price ‘shock’ of 1973 (Slessor 1978; Hammond 2000). In the context of unreliable or expensive energy supplies, the energy required to provide a product or service became a subject of much interest. A predominant aim of energy analysis is therefore to establish the total or ‘gross’ energy requirement (GER) of a product or service (Slessor 1978). This is defined further in the following section. Related aims are to identify energy-intensive activities or fuel/electricity-saving potential, or to provide a physical (rather than monetary) basis for energy forecasting studies (Leach 1975; Roberts 1978). Energy analysis has analogues in many forms, including, for example, the total carbon emissions associated with an activity, which have taken on a particularly high-profile position in the context of national targets for significant cuts in carbon emissions.

While early forms of energy analysis appeared in the late 19<sup>th</sup> century and early 20<sup>th</sup> century (Klimes 1975; Slessor 1978; Spreng 1988), its current basis emerged in the 1970s with the publication of an internationally-agreed set of conventions (IFIAS 1974). It has since been applied widely by academics and government departments, including the UK’s Energy Technology Support Unit, now part of AEA Technology plc, at Harwell (Hammond and Stapleton 2001). It needs to be employed and interpreted with some care, however, as the GER may not necessarily be the most appropriate criteria for assessing energy-related projects (*ibid*).

The process of determining the energy ‘cost’ of a good or service has been controversial, because some commentators saw the emergence of an ‘energy theory of value’ and evaluation of proposals on the basis of energy alone (see, for example, the special issue on energy analysis of the journal ‘Energy Policy’ from December 1975, and its editorial comment; Klimes 1975). In the early days such claims were indeed made by some energy analysts, but there was subsequently a general disavowal of any normative function<sup>2</sup> for energy analysis (Klimes 1975). Rather than prescribing optimal courses for action, it is a descriptive method that aims simply to indicate the energy consequences of an activity (Chapman 1976). Such information can complement that arising from other disciplines, and thus form part of a wider energy-system assessment process.

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<sup>2</sup> Normative economics is concerned with how an economy ought to be run. The main considerations are efficiency and equity. In efficiency terms, it asks whether any given objective could be achieved using fewer real resources. If so, more resources would be left available to achieve other desirable ends. In equity terms, it asks whether the distribution of costs and benefits is desirable given objectives such as equality, fair rewards for effort, and not disappointing people’s reasonable expectations. These aims are not always mutually consistent, and normative economics has to consider the trade-offs between them and between the equity and the efficiency effects of any arrangements (Dictionary of Economics 2009a).

### 2.3.2 Conventions and definitions for energy analysis

Internationally-agreed conventions for energy analysis were established at a workshop convened in 1974 under the auspices of the International Federation of Institutes for Advanced Study (IFIAS 1974). To describe the total energy requirement of a product or service the workshop defined the *gross energy requirement* (GER), which may be described as the sum of all the energy resources that had to be sequestered in order to produce the product or service. Here 'sequestered' is used in the sense of 'set apart', to indicate that energy may be 'tied up' in the finished product in addition to the energy used during production (Roberts 1975). The energy resources that constitute the GER are aggregated in terms of enthalpy, e.g. the enthalpy of combustion (see glossary) for fuels. The IFIAS specified this to be in 'Gross Calorific Value' (GCV) terms (IFIAS 1974).

### 2.3.3 The system boundary revisited

In order to calculate the gross energy requirement of a product or service, both the *direct* and *indirect* energy inputs must be considered. *Direct* energy inputs are those at the point of product or service production, such as heat or work inputs during construction. These energy inputs themselves have *indirect* energy requirements to make them available at that point (e.g. the fuel inputs to a power station). Also to consider are the material inputs to the product or service. These materials have their own energy requirements to be accounted for: direct energy inputs for their processing and transportation and indirect energy inputs embodied in the machines producing them. This process of 'regression' can go on and on, but in practice the energy values usually converge mathematically in a few stages; the truncation error being acceptably small (Slesser 1978; Herendeen 1988). While the energy requirements of energy and material inputs are accounted for, the IFIAS recommended that energy requirements for labour are excluded, at least in industrialised countries (IFIAS 1974).

The aggregation of all direct and indirect energy inputs to the point of a product's production has been described as a 'cradle-to-gate' assessment – from the raw materials to the factory gate. This is extended to a 'cradle-to-site' assessment if transportation requirements are accounted for. The term 'embodied energy' generally refers to either of these situations; in some but not all cases transport is included. A full 'cradle-to-grave' assessment is made when all remaining stages of the product's life-cycle are included: operation; maintenance; decommissioning; and so on (Hammond and Jones 2008).

All energy flows identified for inclusion in the GER are traced back upstream to the extent of the *system boundary*; ideally to the energy resources in their natural form (e.g. coal in the mine or oil in the well), and are quantified at that point in terms of enthalpy. The definition of the system boundary can vary with the purpose of the study, as can the method of quantification in some cases (e.g. nuclear fuels), and therefore they should be clearly defined at the outset as they have a key influence on the results. The research underlying this thesis was concerned with the total resource use required, for example, to produce a micro-wind turbine and enable its subsequent electricity generation, and the following definition of the system boundary applies.

In order to assess *total* energy-resource use, the system boundary is effectively drawn around the Earth; the use of any stored fuel reduces the remaining resource and thus needs to enter the account. ('Account' here is used by analogy with a financial account, where energy inputs are accounted for instead of financial transactions.) This system boundary is self-explanatory in the case of fossil-derived energy forms, a 'capital' resource (Hammond 2004a) that is non-renewable within human timescales. The quantification for the GER is also relatively simple – energy flows should be traced back to their naturally occurring form in the ground and quantified in terms of their enthalpy of combustion. The system boundary is equally self-explanatory for nuclear fuels, though their quantification is more difficult. There has been much debate on the quantification of nuclear fuels, (see, for example, Haldi and Favrat 2006), but here it is done in accordance with a predominant method; nuclear inputs are quantified in terms of the enthalpy change of water (the working fluid for electricity generation) as it is raised to steam by nuclear fission (see, for example, the U.K.'s national energy statistics; BERR 2008a). Renewable fuels (such as biomass) are, in contrast to fossil or nuclear fuels, an 'income' energy form since they are renewed over a short time period, but as a stored resource whose quantity is limited (for example by land availability and suitability), their use should be included in the 'resource-use' account in their natural form; quantified in terms of their enthalpy of combustion. Geothermal energy flows also emanate from within the system boundary, but as a continual flow of energy they are treated as other ambient energy flows as now defined.

With a system boundary drawn around the Earth there are certain other energy forms that are seen as an 'income' (Hammond 2004a) and add to the energy available at any point in the stored fuels. These are the ambient energy flows such as solar irradiation and its derivatives (e.g. wind and wave energy) and energy based on gravitational force (e.g. tidal energy). They are continual (although often variable) and inexhaustible from a human perspective; when harnessed their potential for near-term future harnessing is undiminished. If they are unused, however, the opportunity to harness them is generally lost (though some, for example solar irradiation, may instead be absorbed by plants via photosynthesis and hence stored and possibly used). Since ambient flows are both continual and renewable their use does not need to enter the resource-use account until they have been captured and converted into, for example, useful electrical or thermal energy<sup>3</sup>. At this stage they influence human energy systems and should be included in the account. The electricity required to manufacture a product, for example, needs to be accounted for whether that electricity came from a coal-fired power station or another solar panel, in order to calculate its total energy requirement.

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<sup>3</sup> Conversion efficiencies from ambient energy flows to useful energy will affect, for example, the area of solar panel required to meet a specified energy demand. This may have an associated opportunity cost, but the amount of unutilised solar energy is otherwise not a concern, in contrast to, say, unutilised energy released from a limited quantity of fuel.

Given the preceding definitions, and for clarity, Table 2-2 outlines the energy resources that are included in the GERs presented in this thesis:

**Table 2-2: Energy resources included within a GER and their quantification**

Energy resource	Quantification for GER
Fossil fuels	Enthalpy of combustion
Nuclear fuels	Enthalpy increase of working fluid
Renewable fuels	Enthalpy of combustion
Electrical or thermal energy derived from ambient energy flows	Enthalpy-equivalent

It is worthwhile noting that although the above definition of ‘energy resources’ appear similar to the often-used term ‘primary energy’, there are subtle but important differences. The term *primary energy* is discussed in detail, along with related terminology such as secondary and delivered energy, in Appendix B. It is defined there in accordance with the UK’s *Digest of UK Energy Statistics* or ‘DUKES’ (BERR 2008a) as being ‘drawn (extracted or captured) from natural reserves or flows’. If all energy and material flows originated within the boundary covered by the energy statistics (the unitary state boundary of the UK in this case) the terminology would agree with the requirements outlined above. In such a case all the energy required to extract and make available the ‘primary energy’ would be incorporated into the statistics, for example appearing as ‘energy industry use’. However, many energy commodities are traded internationally, and when they enter national statistics as ‘imports’ any upstream extraction, processing and transportation requirements are not included. This also applies to any material imports. The treatment of imports means that the UK’s ‘primary energy use’ according to DUKES is *not*, therefore, the total energy resource extracted from natural reserves or flows.

The remainder of this thesis uses both the terms *energy resource* and *primary energy*, depending on the situation and data source. The term ‘primary energy’ is used when statistical sources such as DUKES are quoted directly (Figure 3-1, p.36, for example), and it is thus used in accordance with the DUKES definition (e.g. BERR 2008a). When the *gross energy requirement* of the assessed micro-generators is quoted, or the *Energy requirement for energy* as defined below, the numbers are defined in terms of ‘energy resources’ as defined in Table 2-2.

#### 2.3.4 Alternatives to the GER

There are situations in which the gross energy requirement is not the most appropriate quantity, such as where an energy analyst wishes to examine the performance of an isolated process, or where he or she wishes to discount the energy still available in the products of a process. For such cases, the IFIAS workshop defined the *process energy requirement* (PER) and the *net energy requirement* (NER). The process energy requirement is the quantity obtained when the system boundary is constrained to just the process of interest. This is useful when the objective is to track process improvements since it does not include the influence of the resource efficiency of the wider energy system. The net energy requirement is the gross energy requirement minus any energy still available in the product of interest (Slessor 1978 p.135). One type of product that has received particular

interest in these terms is fuel, to which this discussion will return in Section 2.3.7 on ‘net energy analysis’.

As indicated in Section 2.2, although the property *enthalpy* is often used to quantify energy interactions, enthalpy changes can sometimes give a misleading picture of energy interactions (see the coal-fired power station example of Section 2.2.2). The IFIAS workshop discussed alternatives to enthalpy as a measure of energy carriers, and both *Free Energy* and *available work* (exergy) were considered. These similar quantities incorporate the Second Law of Thermodynamics and measure the work potential of an energy carrier with reference to a specified environment. The main difference between the two similar concepts is the definition of the environment. In the case of Free Energy, the environment is defined by an arbitrary but agreed *standard reference state*, whereas in the case of exergy it is the actual environment (albeit in idealised form) of the system under consideration (IFIAS 1974). The latter is therefore more useful in an engineering context. The workshop concluded that there was no unique input, and that it was necessary to adopt a convention. It was agreed that Free Energy often best expressed the objectives of energy analysis, but it was also noted that for most ‘intensive’ fuels (high Free Energy potential per unit mass, e.g. coal and oil) the enthalpy value is similar to the Free Energy value (*ibid*). If the majority of a GER is in the form of fossil fuels, therefore, its enthalpy value would be similar to that of a *gross Free Energy requirement*, or similarly a *gross exergy requirement*. Since in many cases the calculation of Free Energy changes during processes was difficult, at least at the time of the IFIAS conventions, it appears that the discipline commonly referred to as ‘energy analysis’ has subsequently become associated primarily with the use of enthalpy to quantify energy carriers and their upstream sources. It is unclear why available work (exergy) was not recommended since justification against its use was not given by IFIAS (1974), but it is likely that the reason was similar to the case of Free Energy.

Since the time of the IFIAS workshop much research has been undertaken in the use of Second Law concepts, which has increased their potential application. The area of exergy analysis, one avenue of such research, is discussed below in Section 2.4 (p.25), and the technique is used to draw relevant insights during the course of this thesis.

### 2.3.5 Methodologies

A variety of methodologies emerged to calculate the GER, from disciplines including ecology, engineering and economics (Klimes 1975, Slessor 1978, Hammond 2007a). The predominant, conventional forms are known as *statistical analysis*; *input-output analysis*; and *process analysis*, and their application partially or totally determines the system boundary of the study. The techniques have been discussed at length in previous publications, and so are only summarised briefly here (for further discussion see, for example: Bullard and Herendeen 1975; Leach 1975; Roberts 1978; Slessor 1978; and Herendeen 1988). The procedure of environmental *life cycle assessment* follows a similar methodology to process analysis and includes a calculation of the energy resources required by a product or process. This is outlined following the summary of conventional energy analysis methodologies.

Statistical analysis uses a variety of data sources, including Censuses of Production, information from individual industrial sectors, or fuel sales of various forms (Roberts 1978). Within the field of industrial energy analysis, it can provide a reasonable estimate of the primary energy requirements of products classified by industry (Hammond and Stapleton 2001), and it can also rapidly determine certain energy requirements within other sectors, such as the use of residential sales statistics to determine typical household fuel and electricity usage. Statistical energy analysis is thus a ‘top-down’ approach, taking sectorial or national data to characterise the average energy requirement of products or processes of interest. It is limited in scope by the availability and level of disaggregation of data, which also determine the system boundary. For example, consider the energy use of households. The final fuel and electricity usage of the residential sector can be determined and disaggregated by type of energy-carrier (e.g. gas, oil, electricity) from sales records, and are available in national statistics such as the UK’s DUKES publication (BERR 2008e). This same source can be used to determine the total quantity of upstream primary energy that enters the economy to enable this fuel and electricity delivery. DUKES is a very useful source since it provides these forms of data for the majority of the residential sector. However, such datasets have limits to their scope. The UK’s household energy statistics (e.g. BERR 2008e) aggregate all households at a regional or even national level. They also truncate the system boundary at the point that energy flows enter the national economy and hence, in the case of fuels sourced from elsewhere, energy requirements for extraction, processing and transportation may not be included. The system boundary is also truncated at the point of delivery to homes. The different applications of the delivered fuels and electricity may therefore only be estimated indirectly from knowledge of installed appliances, whose conversion efficiencies determine the final ‘useful energy’ available to householders.

Input-output analysis, which can be described as a form of statistical analysis, uses monetary flows between economic sectors as surrogates for material flows (Herendeen 1988). The gross energy requirements of products may then be calculated via knowledge of their material composition. A key advantage of the approach is that the economic ‘input-output’ databases are expansive and enable hundreds of sectors and their constituent commodities to be characterised. The development of input-output analysis rendered estimation possible in areas where other methods would have proved infeasible due to data or time constraints, and thus became an important technique after its inception in the 1970s (see, for example, Bullard and Herendeen 1975). However, even with a large number of commodity categories included, aggregation is still a problem, since commodities within a sector may in fact vary considerably. Furthermore, average data may not be appropriate; the data are typically at least seven years old, reflecting the enormity of the task; and finally, monetary flows may not be an appropriate surrogate for energy flows (Herendeen 1988; Leach 1975; Slessor 1978 p.153). Like statistical analysis, the system boundary is constrained to the available dataset, in this case considering only those material-flows that are measured by economic statistics.

Process analysis is the most detailed and hence potentially accurate of the methods, directly recording all energy use associated with a particular product or activity. It is thus



a 'bottom-up' approach, in contrast to the 'top-down' methods of statistical analysis and input-output analysis. For example, to determine the total energy requirement of a wind turbine, energy-use data would be taken from the manufacturer's factory, along with records of all material and service inputs from other sectors of the economy. Data would then be collected from the suppliers of those inputs, then at the suppliers of the supplier's inputs, and so on, upstream. In principle, the data collection could go on and on, but in practice the energy values usually converge mathematically in a few stages; the error from truncation being acceptably small (Herendeen 1988). Slesser (1978, p.126), for example, suggests that 90% of the energy requirement of a product will be accounted for by truncating at the second 'level of regression' (the energy requirements of the inputs to final process, to be added to the 'first level' which covers the direct, processing energy requirements).

Environmental *life cycle assessment* (LCA) aims to quantify a range of potential environmental impacts of products over their full life-cycle (Udo de Haes and Heijungs 2007). The methodology follows closely that developed for energy analysis, especially that of process analysis. It requires the determination of a balance or budget for the raw materials required by, and pollutant emissions emanating from, the system in question (Allen et al. 2008a). The research underlying this thesis was conducted in collaboration with colleagues carrying out LCA studies: see Allen et al. (2008a) for further details. The specific LCA methodology adopted was the 'Eco-Indicator 95' methodology (see, for example, Frischknecht and Jungbluth 2007), which includes estimates of energy resource requirements and greenhouse-gas emissions. The energy resource requirements are the GER as defined in Section 2.3.2, except that during application of the methodology fuel-energy resources were quantified in Net Calorific Value (NCV) terms, rather than Gross Calorific Value (GCV) as defined by IFIAS (IFIAS 1974). The difference is small for fossil fuels, e.g. Table 2-3, and hence an acceptable deviation from the IFIAS conventions. The GER of the micro-generators assessed in Chapters 5 and 6 were calculated by the collaborating LCA researchers and taken as an input to the research reported in this thesis. The collaboration process is described further in Section 2.6.

### 2.3.6 Closure

Energy analysis is a technique that aims to determine the energy requirements of providing a product or service to society and this is done in terms of enthalpy. The system boundary has a crucial influence on the results of an energy analysis and must therefore be specified clearly. This was done in Section 2.3.3. The information provided by an energy analysis is descriptive – it does not prescribe future action, but rather aims to describe the energy consequences of actions. The technique has many modern analogues, including the total greenhouse gas emissions associated with a product or service.

Energy analysis can be applied to any product or service. Of particular interest in this thesis is the supply of *energy* products (e.g. electricity) to the residential sector, through either the established supply systems or by micro-generation technologies. For such cases the discipline of *net energy analysis* may be applied.

## 2.3.7 Net energy analysis

### 2.3.7.1 Preliminaries

In order to change a society's energy system, investments of various forms are required and, just as with money, energy is invested to ultimately provide or save energy. From the viewpoint of the whole energy system, an energy investment in an energy-supply process or energy-saving technology only makes sense if it provides or saves more energy than it requires (see, for example, Slessor 1978 p.142–146). Such an assessment is referred to as *net energy analysis*, and has a variety of modern analogues such as the net carbon analysis of an activity's life-cycle (the carbon emissions saved by the activity minus the emissions related to that activity).

Two distinct conceptual strands have just been introduced: the first is the analysis of *energy-supply* processes and the *energy products* they deliver, while the second is the analysis of *energy-saving* proposals – of changes in *end-user infrastructure* or *technology*. The former can be referred to as a 'supply-side' assessment, while the latter focuses on the 'demand-side'. In the first case, the concern is usually whether or not the energy contained in the energy product (e.g. fuel or electricity) outweighs the energy requirement of delivering it to the point of interest. In the second, the question is whether or not an investment in an energy-saving technology, such as household insulation, is recouped by the energy subsequently saved.

### 2.3.7.2 Net energy analysis of energy products

Much of the early and high-profile net energy analysis literature focused on the supply-side, investigating the net energy performance of established *energy products* (e.g. oil) and possible complements or alternatives (e.g. nuclear, although of course this is not a direct alternative to oil). Examples and discussion of such studies may be found Chapman et al. 1974; Chapman 1975; Leach 1975; Mortimer 1991; and IAEA 1994. Major catalysts for the development and application of net energy analysis were the two oil crises of the early and late 1970s. Its development reflected the concern that an energy product might be a net energy sink, or that it might become so as it depletes and becomes more difficult to access (see, for example, Slessor 1978). Another driver underlying the development of net energy analysis of energy products was the supposition that the more established discipline of economics might miss such a fact or trend, by setting narrow system boundaries or using indirect units such as prices to measure energy flows (Leach 1975). It was argued that net energy analysis of energy products could therefore aid decision making by providing supplementary information grounded in direct, physical measurements of energy.

Much of contemporary interest in micro-generation technologies is driven by the desire to reduce the use of fossil fuels – the dominant energy source in many countries including the UK – and the associated emission of greenhouse gases. For a micro-generation technology to achieve this, it must save more energy resources or carbon emissions (the main greenhouse gas) than those associated with its life-cycle. A key objective of this research was to calculate whether or not the assessed micro-generators achieve this – whether or not they provide a net energy or carbon benefit. Some relevant

definitions and general methodological issues regarding net energy analysis are now outlined, to facilitate its application later in this thesis.

### 2.3.7.3 *Some relevant definitions*

The gross energy requirement of a given quantity of energy carrier (e.g. a fuel) – the *total* amount of energy resource sequestered when providing that energy carrier to society – is the direct energy requirement of extracting, processing, and delivering it to the point of interest, plus the indirect energy requirement of all associated equipment (amortised as appropriate), plus the energy content of the energy carrier at the point of delivery. When expressed per unit of energy carrier, this value is defined as the *Energy requirement for energy* or ERE (Slessor 1978 p.65–78). The ERE is time, technology and location specific. Slessor (1978) argued that tracking the ERE of an energy resource over time is an effective way of tracing its depletion, although noted that improved (e.g. more efficient) technology can oppose this trend by decreasing the ERE. The direct and indirect energy requirements of energy products also vary by location, for example between countries with differing energy supply systems that support the energy provision process. Similar to the ERE, a *carbon-emission factor* can be defined for an energy carrier to communicate the total carbon emissions associated with its use.

The net energy requirement of a fuel is its gross energy requirement minus its energy content at the point of delivery – it communicates the energy burden placed on the rest of the economy by that fuel. Herendeen (1988) highlighted that this parallels standard economic practice in that the ‘cost’ of using a resource is the cost to the economy – it includes only those inputs taken from the rest of the economy and excludes any ‘external’ costs (e.g. a reduction in remaining resource). In the U.S., Cleveland et al. (1984) defined the ratio of energy delivered to the fuel’s NER as the *energy return on investment* (EROI). Cleveland (e.g. 1992) has also used the term *energy surplus*; the energy content of the fuel minus its NER. These indicators provide complementary information; the EROI is a dimensionless ratio of reward to effort while the energy surplus indicates the absolute magnitude of the fuel’s net energy delivery. The former must be greater than one (the latter must be a positive number) if the fuel in question is to be a net energy source for an economy rather than a sink. A further indicator that again parallels economic practice is that of an *energy payback period*. It is the time taken for the cumulative energy delivered to equal the energy invested. None of these indicators, as defined here, directly address the more global question of the total quantity of energy resource sequestered in delivering the fuel to the point of interest, for which the ERE or equivalent is required. They may, however, indirectly indicate resource-depletion, if this increases the NER over time.

In addition to its application to fuels, net energy analysis has been applied to a variety of supply-side energy conversion technologies, particularly electricity generating technologies (e.g. IAEA 1994). Electricity generation by thermal power plants is, by definition, a net energy sink when the input fuel is included in the account, since this fuel is ‘lost’ and the electricity output is always less in accordance with the Second Law of Thermodynamics (Section 2.2). As a result, many net energy analyses of thermal power plants (such as those reviewed by IAEA 1994) *exclude* the energy content of the fuel

combusted. In this way they can calculate whether or not the direct and indirect requirements of the plant's life-cycle (e.g. production, operation, maintenance and decommissioning), plus the direct and indirect requirements of obtaining and delivering its fuel, are recouped by the generated electricity. The indicators defined in the previous paragraph can then be applied, but once again these will not provide information about the total resource reduction brought about by the generator in question.

The choice between the two fundamentally different approaches outlined above – the first considering total resource use and the second considering the net energy available from an economy's perspective – depends upon the purpose of the study. For example, Cleveland et al. (1984) adopted the second approach in order to investigate the relationship between national energy use and economic activity in the United States, through use of the EROI. This offered a different perspective from standard economics on historical and current economic events, and they concluded that the net energy yield of energy products (shown by the EROI) was a major driver of the U.S. economy. They also showed a marked decline of EROI for all principal U.S. fuels in the decades leading up to the time of the study. They suggested that future economic growth would depend upon the net energy yield of alternative fuel sources, and that biophysical constraints on economic activity may need to be incorporated into standard economic models. (There is a rich body of literature concerning the relationship between energy and the economy that is beyond the scope of this discussion, such as that within Slessor 1978, Ayres and Warr 2005, and Ayres et al. 2007, to name but three.)

The net energy analyses within this thesis have a different objective. They aim to investigate the total quantity of energy resource sequestered in providing energy products, via different supply-technology options, to households. For such an objective, the ERE is more appropriate and is thus used within this thesis.

#### *2.3.7.4 Displaced energy*

When dealing with an energy-saving technology its net energy performance may be determined by comparing the energy it saves (displaces) with its energy investment. This approach can in fact also be applied to an energy-supply technology. In this case the energy-supply technology is seen to displace the established energy system or an alternative proposed supply technology that might be used instead. The energy output of the supply-technology in question is then quantified as the energy displaced from the established or alternative energy system. This 'energy displacement' concept is how a combined heat and power scheme, for example, can be said to 'save' energy; if it uses less fuel than the established system in providing the same energy services.

#### *2.3.7.5 Net energy indicators for ambient renewable technologies*

Net energy analyses of ambient renewable energy-conversion technologies require an extra mention for clarity. Unlike fuel-based conversion technologies, ambient renewable conversion technologies such as solar panels do not have any 'fuel' requirements since their ambient energy inputs are not included in the resource use account. They can, therefore,

provide a net energy benefit (and payback their energy investment) when the total sequestered resource is accounted for, unlike resource-based energy conversion technologies (such as thermal power plants or boilers). When the energy outputs of ambient renewables are accounted for directly (e.g. units of electricity provided), the energy payback period (EPP) is defined in this thesis as the ‘simple’ EPP. When their energy outputs are accounted for in terms of the total energy resource they displace, the ‘displaced’ EPP is produced. Both of these indicators are used within this thesis to describe the net energy performance of the selected micro-generators.

#### 2.3.7.6 *Aggregation of energy flows*

The problematic issue of aggregating different types of energy carrier confronts all forms of energy analysis. This is particularly relevant to net energy analysis since the method compares energy delivered (e.g. electricity supplied) with energy invested from different sources (e.g. coal plus oil).

There are two main options within thermodynamics for measuring and aggregating energy carriers. This first is to measure energy carriers in terms of the First Law, where heat and work interactions are seen as equivalent (Kotas 1985). The second is through the concept of exergy, based upon a combination of the First and Second Laws (*ibid*). An advantage of the First-Law approach is that it is relatively easy to apply. A large body of energy analysis (and net energy analysis) literature has developed over the past forty years on this basis, and similarly it is the approach taken within this research to calculate, for example, the gross energy requirement of the micro-generators under consideration. The disadvantage of the First-Law approach, however, is that it does not recognise that heat and work are dissimilar energy transfers (Section 2.2) – that different energy interactions have differing potentials to provide work.

In thermodynamic terms these differences can be illuminated through the property *exergy*, because it incorporates the Second Law and hence does recognise the differing work-potential of different energy forms. But exergy does not always provide alternative insights to an isolated First Law assessment. When aggregating fossil fuels, energy (enthalpy of combustion) and exergy quantities are similar, as indicated by the IFIAS report (Section 2.3.4). Similarly, when electricity is generated from fossil fuels, energy and exergy inputs and outputs are similar and hence energy and exergy efficiencies are similar (as shown previously in Section 2.2.2). This indicates that when the majority of a gross energy requirement (GER) consists of fossil fuel inputs, whether directly or indirectly (via electricity), the gross exergy requirement (GExR) of a product or service would be a similar quantity to the GER. In the UK, for example, fossil fuels consisted of 92% of the primary input to the economy’s energy system in 2007 (BERR 2008a), and the GER of a UK product or service is thus likely to be similar to its GExR at the present time.

While the view upstream to the overall energy ‘investment’ may be similar for the UK in energy and exergy terms, differences may emerge when looking to reduce that energy investment. This is because, as seen previously in Section 2.2.2 (the coal-fired power station example), individual energy interactions can appear very different in energy and

exergy terms. An assessment of the potential for reduction in the GER was not, however, within the scope of this research. Rather than analyse improvements in the technologies themselves, this research aimed to assess the current form of the technologies as an option for residential energy supply. The focus was therefore upon their likely energy outputs and the implications of this assuming a fixed GER. Should further work aim to reduce the energy requirements of the micro-generators, exergy insights could be drawn upon alongside an energy analysis. Within the context of a life cycle assessment the ‘cumulative exergy demand’ methodology could be useful for this (see, for example, Bösch et al. 2007 and Frischknecht and Jungbluth 2007).

A further and important difference between energy and exergy insights may sometimes exist when looking downstream to the energy provided by a supply technology, or further to the end-uses of energy. Exergy does not provide a different perspective when considering the electricity output of a micro-wind turbine, because electricity can be used to provide either work or heat and hence energy and exergy insights are equivalent. But the heat output of a solar hot water system is of low temperature, and hence it has a low work potential – a low exergy. (These differences are discussed in more detail later in Section 2.4.3.) Assuming similar gross energy and exergy requirements for both technologies, an ‘exergy payback period’ would therefore be similar to ‘energy payback period’ for the micro-wind turbine, but different in the case of the solar hot-water (SHW) system. While this is a valid result within the confines of the comparison of energy output to energy investment, the comparison itself is problematic. This is because the hot water output is a final energy service provided to the end-user, while electricity is an intermediary energy carrier that is later employed to provide a variety of both work- and heat-related energy services. In other words, the system boundaries of the two assessments are different: one extends to end-use while the other truncates at energy delivery to the end-user.

Resolution of differing system boundaries is an important step in enabling a fair ‘net energy’ comparison of supply technologies. One way to achieve this, as adopted in later chapters, is to account for the energy outputs of proposed supply technologies in terms of the energy they each displace at a specified stage in the established supply system, as outlined previously in Section 2.3.7.4. This can be, for example, at the stage of energy delivery to households, or at the stage of the energy resources in their naturally-occurring forms. In either case, since the energy currently delivered by established systems is mainly either fossil fuels or electricity, the latter being based almost entirely on fossil fuels, the energy and exergy displaced by a proposed supply technology would be the same.

Another way to achieve equality of system boundaries is to trace all energy flows to the energy services they ultimately provide. The analysis is then no longer a ‘net energy analysis’ – the comparison of energy delivered or saved to energy invested – but a full energy analysis of final energy services. Net energy concepts such as the ‘payback period’ no longer apply. Instead, energy services – such as a defined volume and temperature of hot water or defined light level over a period of time – are described in terms of their gross energy requirement. The advantage of this approach is that *all* potential for improvement

can be identified, such as efficiency improvements in end-use technologies, rather than just that on the 'supply-side'. The disadvantage of an energy-service analysis is that it is analytically cumbersome. The approach is undertaken in this thesis in some illustrative cases, but a complete analysis of all energy services provided within households was beyond the scope of this work. It has, however, become increasingly apparent during the course of the research that the 'energy service' approach is warranted where a thorough perspective of the improvement potential in energy systems is desired. It is therefore recommended in Chapter 8 that incorporation of end-use considerations be undertaken in future work.

There are many other quality differences between energy flows beyond those recognised by the established laws of thermodynamics. Howard Odum and colleagues proposed *emergy* as an alternative while others have suggested economics-derived quality measures (see, for example, Cleveland et al. 2000.) For brevity these have been excluded here, and a brief discussion has been included instead in Appendix D, where it is concluded that they were not appropriate for the research reported here.

#### 2.3.7.7 Closure

In conclusion, the difficulty of aggregating energy flows confronts all analyses of energy systems – a difficulty that does not appear to have a unique resolution. This may explain why analysts often highlight the issue but do not provide conclusive recommendations for its treatment (e.g. Herendeen 1988). When undertaking a net energy analysis it is therefore necessary to adopt a convention appropriate to the aims of the study and to state it clearly.

An objective of this research was to calculate the net energy performance of selected micro-generators, and the following approach was adopted:

- The gross energy requirement of the micro-generators was calculated (within the collaborative life cycle assessment) in terms of aggregated *energy* quantities. Since the majority of these requirements are in the form of fossil fuels, the gross *exergy* requirement would be similar and was thus not calculated. Since this research did not aim to investigate potential reductions in the gross energy requirement, it was taken as a fixed quantity.
- The 'displaced' energy payback period of the micro-generators is calculated to resolve the issue of differing system boundaries between the solar hot water system and the electricity micro-generators. The 'displaced energy' in this calculation is quantified as the overall displacement of naturally-occurring energy resources that would occur through use of the micro-generators. Since the majority of this displacement is in the form of fossil fuels, energy and exergy values would be similar and hence again, only energy values are calculated.

## 2.4 EXERGY ANALYSIS

### 2.4.1 Background

Energy analysis does not recognise the exergy changes associated with energy transfers, nor how exergy is inevitably destroyed. As just discussed, there are occasions where energy and exergy analyses yield similar insights, and in such cases this thesis therefore presents energy analyses only, for brevity. There are also, however, cases where an exergy analysis provides differing and complementary insights to an energy analysis. Both situations were seen in the example of the coal-fired power station assessment of Section 2.2.2. The overall energy and exergy efficiencies were approximately equal, but within the components of the power plant the exergy analysis identified differing loss mechanisms to the energy analysis, and provided a more realistic assessment of the potential for power plant improvement. Accordingly, this thesis draws insights from exergy analysis only where they add additional and complementary information to energy analysis.

The term ‘exergy’ was suggested by Zoran Rant in 1953 (Haywood 1974), and it has received general acceptance and application since. (Other terms for this quantity or close relatives have included availability, available energy, available work, and essergy; Hammond and Stapleton 2001). Dewulf et al. (2008) have suggested that exergy, as a concept, is more readily understood than that of the more abstract and intangible property ‘entropy’ (another Second Law concept; see Rogers and Mayhew 1992), and Moran (1998) indicates that many experts attest to the pedagogical value of ‘exergy’. Exergy analysis is not, however, strictly needed to identify Second Law issues. Chapman (1975), for example, correctly discerned the waste inherent in using nuclear-generated electricity for space heating rather than for electrical appliances or mechanical drives. He employed First Law energy analysis, but supplemented this via implicit understanding of Second Law issues (Hammond and Stapleton 2001).

Similar to the case of energy analysis, the thermodynamic concepts underlying exergy date back to the 1800s, but the theory did not begin to reach maturity until after 1970 (Sciubba and Wall 2007). Sciubba and Wall (2007) give two reasons for this. First, the publication of concise, clear and stimulating textbooks covering the concept during the 1960s that lay the appropriate foundation, and second, similar to energy analysis; the oil price ‘shock’ of 1973 that caused vastly increased interest in energy-related analysis techniques. The latter formed part of the motivation for a 1979 workshop concerning analysis techniques based on the Second Law (Cambel 1980), although this did not aim to codify the developing technique in the same way as the IFIAS workshop had done for energy analysis (Section 2.3.2). There have since been papers published by individuals calling for, and suggesting, codified terminology (e.g. Kotas et al. 1995; Tsatsaronis 2007), but a general consensus does not yet appear to have been reached.



### 2.4.2 Applications

The concept of exergy has been applied within a variety of disciplines and over a wide range of scales. The more traditional use of exergy analysis is in the fields of engineering and energy systems analysis (Hammond 2004a). It has been applied extensively at the level of individual processes and energy conversion technologies (*ibid*). Reistad (1975), for example, used the technique to quantify the thermodynamic losses in coal-fired power plants, as outlined previously in Section 2.2.2 (p.7). van Gool (1980) highlighted the exergy inefficiency that can occur during the low-temperature heating of buildings and water. Recent reviews of the literature show that exergy analysis is also making contributions in the fields of cryogenics, heat transfer engineering, energy storage systems, and refrigeration plants (Bejan et al. 1996; Bejan 1996; Bejan 2002).

At larger scales than individual plant, exergy analysis has been applied at the urban, sectoral (e.g. industrial), national and even international level (e.g. Balocco et al. 2004; Dincer et al. 2003; Wall et al. 1994; Rosen and Dincer 1997; Ertesvåg 2001; Nakicenovic et al. 1996). At the national level, for example, Hammond and Stapleton (2001) applied exergy analysis to identify the broad potential for energy savings across the UK economy. They concluded that 80% of the improvement potential lay with electricity generation and the modes of energy end-use in the residential and transport sectors. This improvement potential is, however, a theoretical maximum that will not be achieved due to real-world technical and economic constraints. Though it clearly identifies the most significant areas of possible improvement, it is important to supplement such exergy analyses with assessments of technical and economic possibility in order to progress towards a more sustainable energy system.

In order to apply exergy analysis at appropriate points later in this thesis, relevant theory is outlined below. The reader is referred to texts such as Kotas (1985) or Bejan et al. (1996) if a more detailed treatment of the theory is required.

### 2.4.3 Thermodynamic quality

Section 2.2.2 indicated that different energy transfers have differing ‘work potentials’ in relation to a given environment. *Work potential* is also referred to as the thermodynamic *quality* of an energy transfer (Kotas 1985): high quality transfers have a high work potential.

Since exergy is a measure of maximum work obtainable from a system, work transfer is equivalent to exergy transfer in every respect (Kotas 1985). That is:

$$E^W = W \quad 2-2$$

where  $E^W$  is the exergy flow and  $W$  is the work transfer (Rosen and Dincer 1997). The exergy flow across the boundary of a turbine, for example, is thus equal to the work transfer for that turbine, which can be described as a transfer of the highest quality.

The exergy flow associated with a heat transfer at a boundary of constant temperature,  $T_p$ , is determined by the maximum work,  $W_{\max}$ , that could be obtained via ideal conversions when using the environment as a thermal reservoir (Kotas 1985):

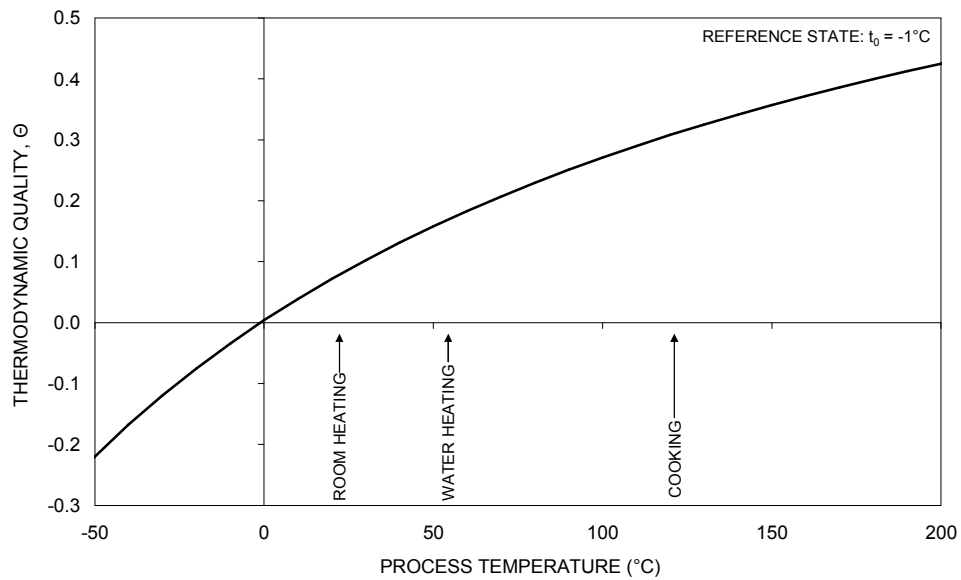
$$W_{\max} = E^{Q_p} = \Theta Q_p \quad 2-3$$

where:

$$\Theta = 1 - \frac{T_0}{T_p} \quad 2-4$$

$E^{Q_p}$  is referred to as the *thermal exergy flow* (Kotas 1985),  $Q_p$  is heat transfer at temperature  $T_p$ , and  $T_0$  is the temperature of the environment.  $\Theta$  is then the ‘quality’ of the transfer: the proportion of the heat that could be extracted as work given ideal conversion processes. It is similar to the Carnot efficiency (Equation 2-1). Heat transfer at low temperature, such as during condensation in the steam power plant example of Table 2-1 (p.8), has a low quality – very little work could be provided by that heat via an ideal conversion device. This indicates that little exergy will be ‘lost’ during the condensation process.

The variation of quality ( $\Theta$ ) with the ratio of process temperature to reference temperature is shown in Figure 2-1. The latter was taken as  $-1^\circ\text{C}$ ; a common winter outside design temperature (Hammond and Stapleton 2001). Indicative heating demands of households are included for illustrative purposes, and all are of a low thermodynamic quality.



**Figure 2-1: Thermodynamic quality of household heating processes**

Different energy forms have different thermodynamic qualities, depending on their mode of storage (Kotas 1985). Mechanical and electrical energy have the highest possible thermodynamic quality (a quality of one) because through ideal conversions they can be fully available as work. The quality of chemical energy depends upon the substance in

question but can also be high and approximately equal to one. That is, through ideal conversions all the energy could be converted into work. Table 2-3 shows the thermodynamic quality of a variety of residential fuels (chemical-energy carriers) – the ratio of their chemical exergy ( $E^{CH}$ ) to their *enthalpy of combustion* in Net Calorific Value (NCV) terms.

**Table 2-3: Typical values of  $\Theta$  for selected residential fuels**

Fuel*	GCV* (MJ/tonne)	NCV* (MJ/tonne)	$\Theta = E^{CH}/\text{NCV}^\dagger$
Residential household coal	30.5	29.0	1.06–1.10 (Different types of coal)
Fuel oil	43.6	41.5	1.04–1.08 (Different fuel oils and petrol)
Natural gas; consumed (1)	39.4 (2)	35.5 (2)	1.04±0.5%
Residential wood (3)	13.9	12.3	1.15–1.30

\* Source: DUKES (BERR 2008a p.211)

† Source: Kotas (1985 p.269)

(1) Home produced and imported gas. This weighted average of calorific values will approximate the average for the year that householders see quoted on their gas bills. It can also be expressed as 10.948 kWh per cubic metre.

(2) MJ per cubic metre, rather than MJ per tonne

(3) Average figure covering a range of possible feedstock; at 25% moisture content. On a 'dry' basis; 18.6 GJ per tonne.

A large proportion of the energy used in households involves the use of fossil fuels or electricity for space or water heating. Since the thermodynamic quality of these inputs is high, and the quality of the subsequent heat transfer is low (Figure 2-1), it is clear that there is a large degradation in quality during the conversion processes; a large exergy destruction. Quality degradation – i.e. exergy destruction – is the result of the irreversibilities associated with a process, which take a number of forms.

#### 2.4.4 Irreversibility and exergy destruction

Kotas (1985) describes the two groups of phenomena found in irreversible processes. The first are *dissipative processes*; the direct dissipation of work into internal energy of the system, where fully organised macroscopic work is converted into microscopic energy associated with the random motion of the molecules. Causes of such dissipation include solid or fluid friction, mechanical or electrical hysteresis, and ohmic resistance. The second group of phenomena are associated with *spontaneous non-equilibrium processes*. This is where a system in a state of non-equilibrium tends to move in an unrestrained manner towards a state of equilibrium. Examples are spontaneous chemical reactions (such as combustion), free diffusion (mixing), unrestrained expansion and unrestrained equalisation of temperature.

Irreversible processes have a mixture of phenomena from the two groups. In combustion, for example, there are irreversibilities associated with the mixing of the reactants, spontaneous chemical reaction, fluid friction and heat conduction over a finite temperature difference. In some cases one form of irreversibility can cause another, such as in the case of a mechanical brake where work is dissipated by friction into the brake-

material, and its increased temperature subsequently causes heat transfer to the environment and a re-equalisation of temperature (*ibid*).

There are thus two conditions for reversibility (Kotas 1985):

1. the system passes through a series of equilibrium states; the process is performed 'quasi-statically', and
2. dissipative processes are absent

Since neither of these conditions is met during a real-world process, all processes have a combination of irreversibilities and exergy is always destroyed. An analyst will often therefore aim to quantify *how much* exergy is destroyed during a process and to ask *is this avoidable?* Exergy analysis addresses the first, identifying the locations, causes, and magnitudes of exergy destructions and losses within a system. More advanced techniques such as *thermodynamic optimisation* (e.g. Bejan et al. 1996) then aim to provide practical guidance for reducing any avoidable destructions and losses. Two significant sources of exergy destruction are combustion and heat transfer, and since they currently underlie the majority of human energy use, they are now considered in more detail.

#### 2.4.5 Combustion and heat transfer

The detailed thermodynamic mechanisms involved in combustion processes are not well understood (Hammond 2007b), but they are clearly a significant source of irreversibility and hence exergy destruction. Dunbar and Lior (1994) found that about one-third of the exergy in the input fuel is destroyed during the combustion process used in electrical power plant. This agrees with Reistad's analysis of U.S. coal-fired power plant (see Table 2-1, p.8), which indicated a 30% exergy loss during combustion (assumed to mean destruction in terms of the definitions outlined in Section 2.2.2). Similarly, Nishida et al. (2002) showed that exergy destruction in gas-turbine combustors was 20–30%; the largest loss of all components, while Caton (2000) found exergy destruction to be 5–25% for idealised (adiabatic) spark-ignition engine cylinders.

In a simple combustion process – an exothermic chemical reaction – the reactants are usually air and fuel and the products mainly a mixture of common environmental substances. Kotas (1985 p.148–150) indicated that since combustion processes are often accompanied by heat transfer as well as fluid friction and mixing, there is usually more than one form of irreversibility present. Indeed, Dunbar and Lior (1994) identified three hypothetically distinct sub-processes involved during the combustion process they modelled. These were: 1) combined diffusion/fuel oxidation; 2) 'internal thermal-energy exchange' (heat transfer); and 3) the product constituent mixing process. The internal heat transfer was found to be the most significant source of exergy destruction, accounting for three-quarters of the total, while the chemical reaction (the fuel oxidization) was in fact quite efficient; an exergy efficiency of 94–97%. Som and Datta (2008) agree with this account, by stating that the most important way of minimising exergy destruction within combustion is to reduce the irreversibilities in internal heat transfer. They go on to say that combustion should be controlled to occur with the minimum possible temperature

gradient in the combustor, which can be achieved through preheating, fuel-air staging, and controlling jet velocities. Nishida et al. (2002) also noted that increasing the inlet temperature led to a reduction in the overall exergy destruction.

Heat transfer is also a significant source of irreversibility. Reistad (1975), for example, indicated that 15% of the exergy destruction in the coal-fired power plant was due to heat exchange in the steam generator (Table 2-1, p.8). Combining this with the destruction due to combustion indicated above shows that 45% of the exergy in the input fuel is destroyed by the time it has been converted and transferred into the working fluid. This is a significant proportion (73%) of the overall exergy destruction associated with such electricity generation, so clearly combustion and heat transfer are major sources of irreversibility in this case.

In the case of space heating, Nieuwlaar and Dijk (1993) found heat transfer within a central-heating boiler to be the largest source of exergy loss (again, taken here to mean 'destruction'). This process is summarised in Table 2-4, which indicates that the exergy loss associated with boiler heat transfer (between the combustion products and the space-heating medium) are 61% of the exergy input. They highlighted, however, that the absolute losses – the right-hand column – do not always reflect the most exergy inefficient processes. Due to losses in previous operations, downstream operations receive a relatively lower throughput and hence exhibit lower absolute losses. This has led Tsatsaronis (2008), among others, to highlight the need to consider the relative position of a sub-process when analysing exergetic performance.

**Table 2-4: Exergetic performance of components in a central-heating boiler system**

Process	Exergy efficiency	Exergy loss (fraction of total input)
Combustion	73%	27%
Boiler heat transfer	16%	61%
Radiators	28%	8%
Total losses		96%

(Source: adapted from Nieuwlaar and Dijk 1993)

Combustion and heat transfer are intimately linked; successful combustion releases heat at a higher temperature than the surroundings. The foregoing indicates that the processes of combustion and heat transfer (and their sub-processes) form the majority of the exergy destruction associated with electricity generation and space (or similarly water) heating.

#### 2.4.6 Thermodynamic optimisation and thermoeconomics

Once exergy destruction has been identified, the technique of *thermodynamic optimisation* (e.g. Bejan et al. 1996) relates it to the physical characteristics of the system; its finite dimensions, material constraints, and finite time-intervals of operation (Bejan 1996). This incorporates awareness of the technical constraints imposed by the real world upon the process under consideration, which for thermal systems requires the incorporation of the disciplines of heat transfer and fluid mechanics. The process thus distinguishes between

unavoidable and avoidable exergy destructions, enabling attention to be focused upon the latter. The technique of *thermoeconomics* (e.g. Bejan et al. 1996) can then incorporate the existence of economic constraints into the optimisation process, to establish which process improvements would be most cost-effective.

Bejan et al. (1996 p.159–162) indicate that the majority of the exergy destruction associated with combustion and heat transfer is unavoidable, although they give guidelines for the minimisation of the small proportion of avoidable destructions. The dominance of unavoidable destruction is due to the nature of the irreversibilities: spontaneous chemical reaction; diffusion; and particularly heat transfer through a finite temperature difference are intrinsically irreversible (Kotas 1985 p.71–72). It is therefore good practice to minimise the use of combustion and heat transfer wherever possible, although of course this is difficult since they are both necessary where the usual methods of fuel combustion are concerned.

#### 2.4.7 Quality matching

While the techniques of thermodynamic optimisation and thermoeconomics can enable the practical optimisation of a process within technical and economic constraints, they only consider trade-offs for the configuration of the process in question (Bejan et al. 1996 p.5). They generally cannot identify the existence of alternative configurations nor fundamentally different solutions to the same problem. One technique that can aid this broader approach is that of *quality* (or *exergy*) *matching*, advanced by van Gool and colleagues (see, for example, van Gool 1987 and Nieuwlaar and Dijk 1993).

Van Gool (1987) considered it useful to describe energy-conversion processes as the interaction of an energy donor (supply) and energy accepting (demand) system. The aim of quality matching is then to match the quality of the supply to the quality of the demand, and thus minimise the exergy destruction associated with the energy conversion process. The heat cascading examples given earlier in Section 2.2.3 (p.8) are examples of the efficiency gains made possible by quality matching. Further discussion of quality matching will be given in Section 4.7 (p.82).

## 2.5 THERMODYNAMICS SUMMARY

Thermodynamics provides a physical basis for the measurement of energy flows. The First Law indicates that energy is always conserved; that the energy output from a system in steady-state always equals the energy input. This enables the technique of *energy analysis* to trace energy flows from their natural forms to their derivative final products or services. The Second Law, however, indicates that the thermodynamic quality of an energy flow – its potential to do work – is progressively diminished as it flows through an energy system. This is illuminated by the concept of *exergy*, which, in contrast to energy, is not generally conserved but rather progressively destroyed. *Exergy analysis* recognises this process and, by providing information about the departure of real-world energy interactions from the ideal case, can give complementary guidance towards more effective energy systems. This must, however, be tempered with an appreciation of real-world constraints such as technical and economic limits to improvement.

Since the majority of the energy used within the UK is based upon fossil fuels, including electricity derived from fossil fuels, there are many cases where energy quantities are similar to exergy quantities. In such cases, only energy analyses are presented within this thesis. Insights *are* drawn from exergy analysis, however, where they provide extra and complementary information regarding both residential energy provision and micro-generation performance.

The concepts of the physical *life-cycle* of a product or service and the need for a clearly defined *system boundary* are key elements of much environmental problem-solving, and such is the case in an energy analysis. Both have been discussed and defined within this chapter (Section 2.3.3).

The energy analyses presented later in this thesis take a variety of forms. On the supply-side, net energy analyses are presented for the established methods of commercial energy supply (Chapter 3) to give context to the subsequent net energy analyses of a selection of micro-generators for household energy provision (Chapters 5 and 6). The net energy analyses of micro-generators are built up from their constituent parts. First, estimates of the energy output of each micro-generator are presented, along with the associated energy displacement from established systems. Second, the gross energy requirement of the micro-generator in question is discussed and then, by comparison of this value with the energy output estimations, a ‘net energy’ assessment is provided. The associated ‘net carbon’ performance of the micro-generators is also assessed.

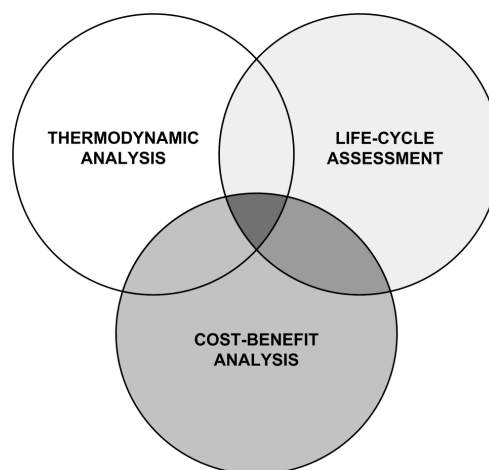
The present chapter has highlighted that care must be taken with the interpretation of net energy analysis results, since the system boundary is usually truncated at the delivery of energy to households. An analysis of energy use within households is therefore presented in Chapter 4. It is presented for two reasons. First, it provides context for the energy outputs of the micro-generators (e.g. how much of the demand can the micro-generator meet?). Second, it enables an understanding of the demand characteristics of

households, which gives an important perspective on supply-side options such as micro-generators and the established methods of energy supply.

## 2.6 AN INTEGRATED APPROACH FOR SUSTAINABILITY ASSESSMENT

Any move towards more sustainable energy use requires a complex balance of economic, social, technical and environmental concerns (Section 2.2.5). This complexity indicates that an assessment of energy systems should draw upon numerous disciplines for analysis purposes. Such an approach was advocated by Hammond and Winnett (2006), who proposed an integrated approach involving thermodynamic analysis, environmental life cycle assessment (LCA), and economic cost-benefit analysis (CBA). These were subsequently applied together by Allen et al. (2008a, 2008b; both reproduced in Appendix E). The thermodynamics element is the focus of this thesis, with carbon assessments playing a complementary role. Key linkages between this element and the others are outlined below.

The three methods used in the integrated appraisal process are represented by Figure 2-2. The overlaps of the Venn diagram indicate an exchange of information between the methodologies, and therefore that the process as a whole benefits from the collaboration. For example, the micro-generators energy-output estimates reported in this thesis were passed to the LCA and CBA researchers, since such energy outputs have a crucial effect on those assessments. Similarly, the LCA included an estimation of the embodied energy and embodied carbon of the micro-generators, and initial estimates of the energy-resource and carbon savings of the micro-generators (which were later updated by the present author). These data were used in this thesis when estimating the net energy and carbon effect of the micro-generators (presented in Chapters 5 and 6).



**Figure 2-2: Elements of the integrated appraisal methodology**

The integrated appraisal, carried out at the University of Bath, was itself part of a wider research initiative across several universities and industrial partners as part of the EPSRC-led SUPERGEN 'Highly Distributed Power Systems' (HDPS) Consortium. The consortium as a whole has involved a wide variety of disciplines and collaborations, and some recent publications have been brought together in a special issue of the Journal of



Power and Energy, published by the UK's Institution of Mechanical Engineers (see Burt et al. 2008). The present author, and hence the research underlying this thesis, benefited in many ways from the interchange made possible by the HDPS consortium. The range of consortium 'workshops', for example, provided an invaluable insight into some of the challenges faced by practitioners from other disciplines (e.g. electrical engineering and further economics issues) in a move to a more distributed energy supply system. Although generally outside the scope of the research reported in this thesis, such context was extremely useful to the research process. An example of a specific interchange that benefitted the present author regarded the use of inverters for grid-tied micro-wind turbines. The feedback received from electrical engineering colleagues at the University of Strathclyde, indicated in Section 5.4.4.4 (p.106), greatly facilitated the treatment of inverters in the micro-wind output estimation methodology.

## CHAPTER 3

# FUEL AND ELECTRICITY SUPPLY TO UK HOUSEHOLDS

### 3.1 INTRODUCTION

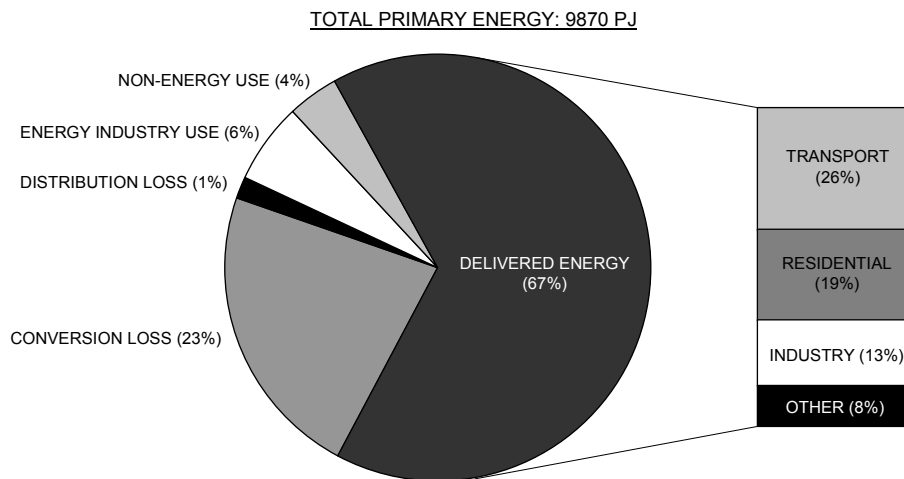
The micro-generators assessed in Chapters 5 and 6 are (partial) alternatives to the established energy-supply systems. They can thus decrease a household's use of conventional energy resources – mainly fossil fuels – and reduce the associated carbon emissions. To give context to the micro-generator assessments, and to facilitate an estimation of the energy-resource and carbon savings they can enable, an analysis of the predominant fuel and electricity supply systems is required. This chapter addresses this need. Brief overviews of the historical development of the systems are given, to give important context to their present characteristics, while focus is placed on the current energy-resource requirements and carbon emissions associated with their use.

### 3.2 OVERVIEW OF ENERGY SUPPLY IN THE UK

The UK's energy supply system, like many others around the world, is based overwhelmingly on fossil fuels – they accounted for 92% of total primary energy supply in 2007 (BERR 2008a; Table 1.1). Of the remainder, nuclear inputs constitute 6% and renewable and waste inputs 2%.

The UK is a net importer of the dominant primary fuels (coal, primary oils, and natural gas). In the early 1970s the over 50% of the primary fuels used were imported, but by the early 1980s the UK had become a net exporter due to massive developments in North Sea oil and gas production (BERR 2008b). After a short period of marginal importing between 1989 and 1992, the UK export level increased again and reached a peak in 1999; a level equivalent to 21% of consumption at that time. Production has declined since that point, however, and the UK became a net importer at 4.5% of consumption in 2004. The trend continued, and during 2006–07 the UK was importing more than 20% the primary fuels that were used (*ibid*).

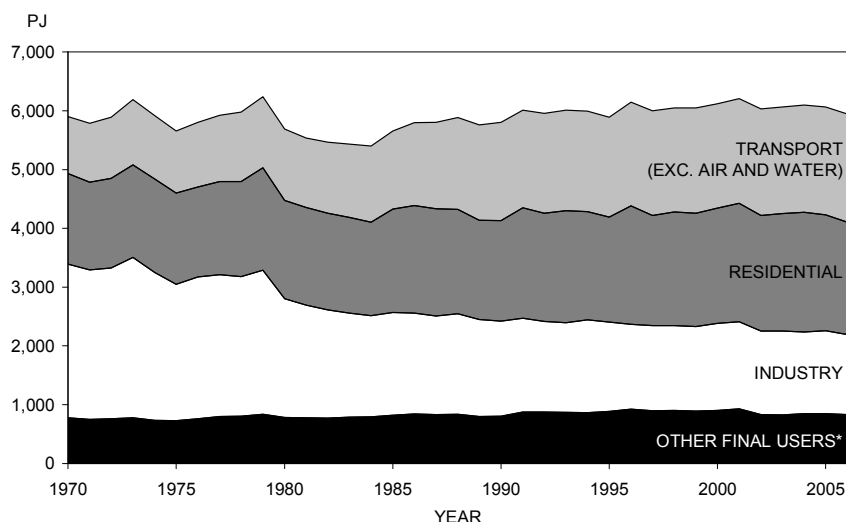
Total primary energy use in the UK was 9870 PJ in 2007, as shown in Figure 3-1. This quantity is in terms of enthalpy, and any fuels included are quantified in GCV terms. 23% of the primary energy input was lost during energy conversions (93% of which occurred during conversion of fuels into electricity), while the energy industry used 6% and 1% was lost during distribution to end-users. 1840 PJ (19% of primary input) was ultimately delivered to and used within the residential sector.



**Figure 3-1: Primary energy use in the UK, 2007**

(Source: BERR 2008a)

Figure 3-2 shows aggregated delivered energy use for each end-use sector back to 1970. Both the absolute value of delivered energy used by the residential sector and its percentage share of the total have risen slightly since 1970, the latter settling at around 30% since the early 1980s.



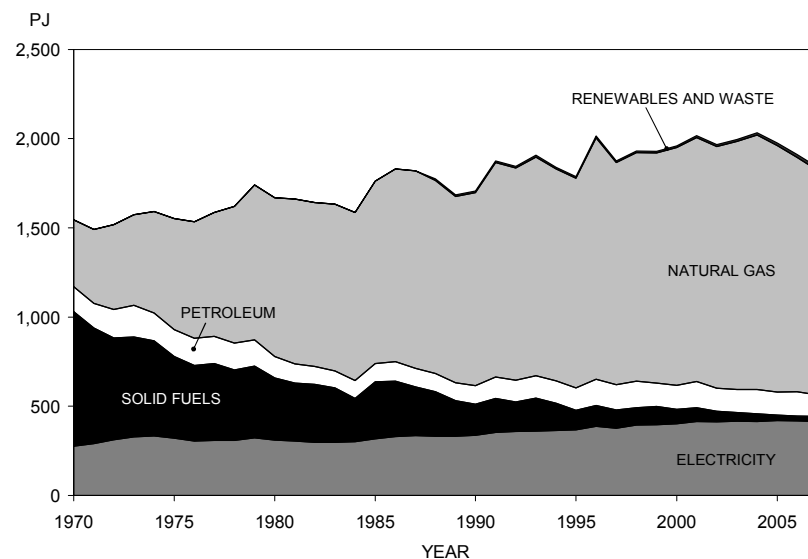
**Figure 3-2: UK delivered energy use by sector, 1970–2006**

(Source: BERR 2007)

\* 'Other final users' is mostly the commercial and public sectors

Aggregated primary and delivered energy values, as presented in Figure 3-1 and Figure 3-2, are useful to provide an introductory overview, but they sacrifice detail concerning the underlying energy forms. Figure 3-3 therefore breaks down the delivered energy use of the residential sector into its constituent energy carriers; mostly fuels and electricity. It shows that natural gas is now the main energy carrier used by households while electricity forms most of the remainder. The fuels used to generate the electricity are shown later in Figure 3-7 (p.47). Both energy carriers are delivered through national

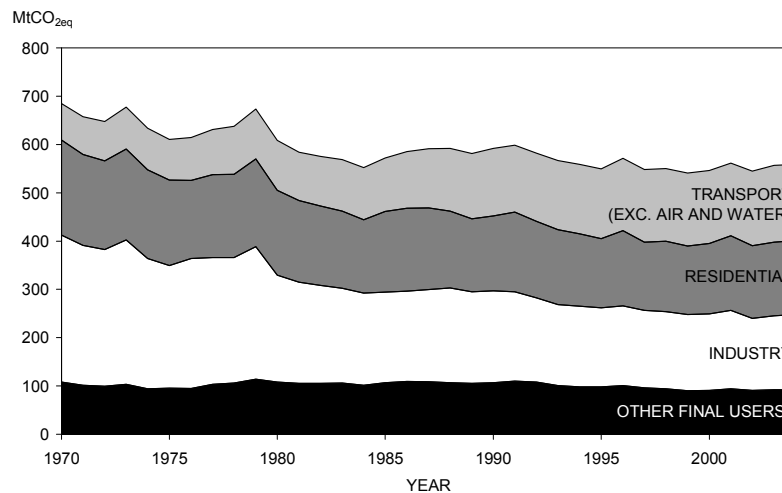
transmission networks operated by private industries. The process of privatisation began in the late 1980s, and deregulation occurred in 1999 so that all consumers, both domestic and business, are free to choose their gas or electricity supplier (Allen et al. 2008c).



**Figure 3-3: Delivered fuel and electricity use of the residential sector, 1970–2007**  
(Source: BERR 2008e)

Upstream losses associated with the use of delivered energy may be allocated to each end-use sector to determine each sector's primary energy requirement. For the residential sector, the 1840 PJ of delivered energy used in 2007 required a primary energy input of 2820 PJ (29% of the total primary input). The major reason for the disparity between primary and delivered energy is the losses that occur during electricity generation. These accounted for 87% of the conversion and transmission/distribution losses shown on Figure 3-1. The UK's carbon dioxide emissions can be allocated to end-user sectors in a similar manner to primary energy. This is done in Figure 3-4, which shows that since 1970 the carbon dioxide emissions attributable to the residential sector have reduced by 22%, totalling 153 million tonnes of CO<sub>2</sub>-equivalent in 2004 (27% of the UK's total).

The relative stability of the residential sector's delivered-energy demand (Figure 3-2) and the reduction in carbon emissions (Figure 3-4) have been achieved in spite of an increasing population, rising household numbers, increasing numbers of energy-using products in homes, and increasing standards of comfort such as higher internal temperatures (Shorrock and Utley 2003; Owen 2006). This has been mainly due to energy efficiency improvements and fuel switching, both within households and, upstream, for centralised electricity generation.



**Figure 3-4: Carbon dioxide emissions by sector, 1970–2004**

(Source: DEFRA 2007)

\* 'Other final users' is mostly the commercial and public sectors

Energy efficiency improvements in the housing stock since 1970 have been substantial, and have included increasing levels of loft, cavity-wall and hot-water-tank insulation, increasing use of double glazing, and the use of more efficient heating systems. In the case of space heating, for example, Utley and Shorrock (2008) estimate that more than twice as much delivered energy would be used now had it not been for the efficiency measures implemented. Upstream, the average conversion efficiency of primary fuels into electricity has also increased, from approximately 27% in 1970 to approximately 35% since the mid-1990s (Figure 3-7, p.47).

The substantial fuel-switching within the residential sector is clear on Figure 3-3, where there has been a move away from carbon-intensive solid fuels (mainly coal) and towards the use of natural gas. Fuel switching has also occurred upstream for electricity generation, where natural gas and nuclear fuels have become increasingly important (this is shown later on Figure 3-7, p.47). There are a variety of reasons for these switches, including fuel price volatility, energy market liberalisation, and environmental/health concerns (e.g. a move to 'smokeless fuel' use instead of coal within the home). A detailed discussion of the development of the UK energy sector (1945–1997) may be found in Hammond (1998).

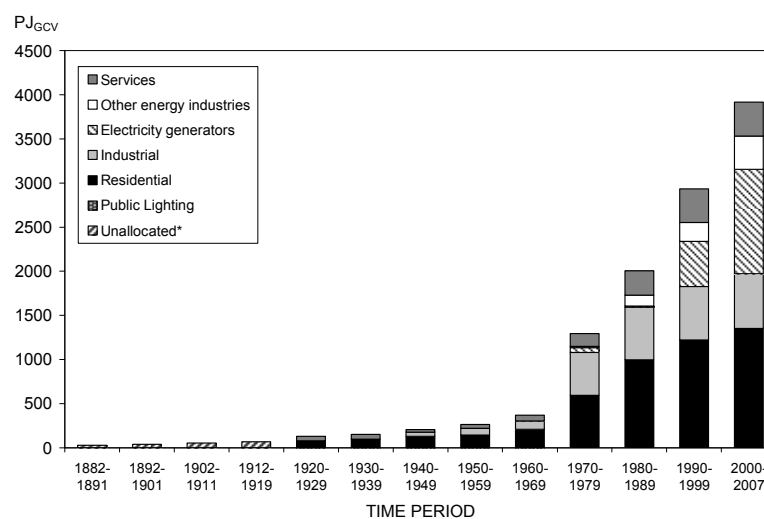
The natural gas and electricity supply systems are the predominant modes of commercial energy delivery to UK households. The micro-generators analysed in Chapters 5 and 6 would reduce the use of these established systems, and each unit of delivered fuel or electricity displaced will represent an energy-resource and carbon-emission saving. In order to estimate the overall saving, the *Energy requirement for energy* (Section 2.3.7.3) and *carbon-emission factor* for both fuels and electricity are needed. All are estimated within the remainder of this chapter.

### 3.3 FUEL SUPPLY TO UK HOUSEHOLDS

The main fuels used in residential sector are natural gas, oil and a small amount of solid fuel (mostly coal). Since natural gas is by far the most dominant fuel (Figure 3-3), this section focuses upon gas supply to households.

#### 3.3.1 A short history of natural gas supply in the UK

Figure 3-5 shows that gas has been used in Britain since the beginning of the 19<sup>th</sup> century, when it was used almost exclusively for lighting (DTI 2001a). Coal was the primary fuel used to produce gas – town gas – by high-temperature carbonisation (the heating of coal in retorts and the injection of steam). From the 1940s the predominant use of gas was for space heating, process heating and cooking within the residential, service and industrial sectors (Figure 3-5); lighting by then being supplied by electricity. The 1960s saw an increasing quantity of oil used to produce gas, and traditional town gas was supplemented by gas from coke ovens, blast furnaces and also methane imported from the Algerian Sahara. In July 1967 a substantial extraction of natural gas from the southern North Sea began to transform the gas industry; a national transmission system was developed and four times more gas was used in the 1970s than in the 1960s. Since 1979 Britain has used exclusively natural gas, some being extracted with and separated from oil from the northern North Sea to supplement other sources. The UK has imported Norwegian natural gas since 1977, and since that time has fluctuated between a net importer and a net exporter of gas. The advent of the UK-Belgium pipeline in the late 1990s has tied the UK gas market more closely to that of the rest of Europe and its price mechanisms (where gas prices are contractually linked to the price of oil), and since 2006 the UK also had access to gas from the Netherlands (*ibid*). Since 2004 the UK has been an increasing net importer of gas (BERR 2008a), and in 2007 imports accounted for 21% of the gas available for inland consumption (BERR 2008b). In the period 2000–2007, the residential sector used 35% of all gas used in the UK; the largest proportion of all sectors, and electricity generation drew the second largest proportion at 30% (Figure 3-5).



**Figure 3-5: Energy content (GCV) of gas used in the UK by different sectors, 1882–2007**  
(Source: BERR 2008i)

\* The 'unallocated' category is likely to in fact be 'public lighting' (see the discussion above based upon DTI 2001a)

### 3.3.2 The average ERE of natural gas

The changing sources and types of gas used have affected its average *Energy requirement for energy* (ERE). The ERE is the *total* energy-resource requirement for a unit of delivered energy, which means the system boundary should extend back to the energy resources in their natural form and all stages of the supply system's life-cycle should be included (amortised in some appropriate manner). In many publications, however, the system boundary may be unclear and is often truncated at the national boundary, and it is also often unclear whether or not all life-cycle stages are considered. An advantage of these publications, however, is that they can provide long-term data with which to build up a picture of the ERE over time. As a result, the following discussion begins with a 'pseudo-ERE' calculated by or from UK energy statistics. These statistics do not directly include all life-cycle requirements, nor do they include any upstream requirements for imports, and therefore a recent and more complete ERE is later estimated for comparative purposes.

When gas was made from other fossil fuels the energy required for a unit of gas was high, because a large part of the energy content of the input fuel was lost in the transformation process (DTI 2001a). The DTI estimated that in the 1930s the energy content of the gas produced was typically only a quarter of the energy content of the input fuels; a pseudo-ERE of 4 for the gas. Since the advent of natural gas, transformation losses have ceased since natural gas is used in the form it is extracted, but there are still energy industry uses of gas and distribution losses.

Statistics regarding gas flow through the UK economy for 2007 are summarised in Table 3-1, along with the calculated pseudo-ERE. Because the latter is calculated all in terms of natural gas, it would be the same whether in terms of GCV or NCV (because it is a dimensionless ratio). 'Transformation' and 'non-energy use' were subtracted from the total primary demand because they are not associated with the delivery of gas to end-users, and the remainder divided by the final delivered gas. Thus, energy industry use and losses mean that 1.13 of primary gas are required for every unit of gas delivered to the end-user. The majority of the excess gas was used for oil and gas extraction. The pseudo-ERE was also calculated for the period 1998–2006, and was found to be 1.12 in the late 1990s and 1.13 since 2000. Put another way, since the late 1990s approximately 88–89% of the primary gas entering the UK economy has been delivered to end-users.

**Table 3-1: Gas supply in the UK and its pseudo-ERE, 2007**

Gas industry information	PJ <sub>GCV</sub>
Total primary demand	3810
Transformation (electricity generation)	1350
Non-energy use	37.7
Energy industry use, of which:	268
Oil and gas extraction	(235)
Petroleum refineries	(12.2)
Coal extraction	(0.328)
Blast furnaces	(2.59)
Other	(18.0)
Losses	43.5
Final delivered gas, of which:	2150
Residential sector demand	1260
Pseudo-ERE of delivered gas	1.13

(Source: Adapted from BERR 2008a; Table 4.1)

This pseudo-ERE is a simplification. Some of the issues not considered in Table 3-1 are: that any electricity-use within the gas industry is not included (which would increase the ERE); that some of the gas used during oil and gas extraction should be apportioned to oil and any gas subsequently used for electricity generation (which would decrease the ERE); and that the other ‘energy industry use’ categories should not necessarily be apportioned here (which again would decrease the ERE). These problems are difficult to resolve, since the gas industry is not a separate entity but rather is inextricably linked to other parts of the economy and energy industries.

M. McManus, a researcher collaborating with the present author (e.g. Allen et al. 2008b), used the life cycle assessment (LCA) database Ecoinvent (v1.3; Swiss Centre for Life Cycle Inventories 2007) to provide data with which to establish a more complete ERE than that enabled by the UK’s annual national energy statistics (Table 3-1). The LCA data aims to incorporate the total energy requirement of a unit of delivered energy carrier, including all energy to extract, transport, (process where appropriate) and deliver that energy carrier. Average values are used, which means, for example, that a value generated for coal will be an average of all different types of coal commonly used in the situation in question (M. McManus, University of Bath, 06/04/2009, personal communication).

The LCA-derived ERE for natural gas was 1.22 MJ<sub>resource</sub>/MJ<sub>delivered</sub> (NCV), an increase of 8% from the pseudo-ERE above. This means that 1.22 units of naturally-occurring energy resource are sequestered (extracted) for each unit of delivered natural gas. McManus also provided data with which to estimate the ERE of oil used by households, which equalled 1.39 MJ<sub>resource</sub>/MJ<sub>delivered</sub> – notably higher than natural gas.

Similar to the ERE, a carbon-emission factor may be estimated for each unit of delivered fuel. These factors include the emissions that occur when the fuel is subsequently burned within households, similar to the ERE that includes the energy content of the fuel delivered. The LCA-derived figures for natural gas and oil were 0.07 and 0.09 kgCO<sub>2eq</sub>/MJ<sub>delivered</sub> (NCV) respectively (0.24 and 0.33 kgCO<sub>2eq</sub>/kWh<sub>delivered</sub>). Again



these incorporate upstream emissions associated with the extraction, transportation etc of the fuels in question.

The ERE and carbon-emission factor are average values – they represent the overall energy-resource extraction or carbon emissions associated with an average unit of fuel. In Chapter 6 these values are multiplied by the gas or oil savings enabled by a solar hot-water (SHW) system, in order to calculate the overall energy-resource and carbon savings enabled by that system. The use of average EREs and carbon-emission factors is a simplifying assumption, because the SHW system in fact has a marginal effect on the gas or oil supply systems that may not correspond to the average value. Any error associated with the average value will be relatively small, however, since the majority of the overall energy-resource use and carbon emissions actually occurs within the household. Another assumption made here is that the average values will remain constant over the next few years, for example when calculating the displaced energy payback period of the SHW system (Section 6.5.5.4). Both assumptions are made in accordance with other contemporary literature that has made estimations of fuel savings or usage by micro-generators: see, for example, Peacock and Newborough (2005); Market Transformation Programme (2008); and Hawkes and Leach (2008).

### 3.3.3 The exergetic performance of fuel supply

The discussion so far has quantified energy flows within the energy supply system in terms of the First Law of Thermodynamics; in terms of energy that is always conserved. Chapter 2 showed that this approach does not recognise the thermodynamic quality of energy flows – their potential to do work. An application of Second Law concepts is required for this purpose, and the property *exergy* is a useful vehicle for this. The thermodynamic ‘quality’ of a fuel is defined as the ratio of its exergy value to its enthalpy of combustion (Section 2.4.3). Table 2-3 (p.28) showed that the thermodynamic quality of residential fossil fuels, in terms of their net calorific values, is approximately equal to one in all cases, and hence the exergy of gas (and many other fuels) is similar to its enthalpy of combustion.

Since natural gas is now pumped straight from its source to the end-user without undergoing transformation, the exergy losses up to the point of delivery are approximately equal to the energy losses, and the exergy delivered is approximately equal to the energy delivered. An *exergy requirement for exergy* would therefore be similar to the *Energy requirement for energy* and is therefore not presented here. It can be anticipated that energy and exergy perspectives will begin to differ significantly, however, when the final, useful energy delivered to end-users by fuels are considered, since much of this useful energy is low temperature heating. This is discussed in Section 4.7 of the following chapter.

### 3.4 ELECTRICITY SUPPLY TO UK HOUSEHOLDS

#### 3.4.1 Electricity: a very different energy carrier

Units of electricity are counted and summed in national statistics just like the fuels that dominate the primary energy input (e.g. BERR 2008a). Electricity is, however, a very different energy carrier to a fuel, and there are some important distinctions between the two that must be highlighted before this section commences.

A fuel is a stored form of energy that can be released as heat whenever and wherever it is required. The distribution and availability of fuels – particularly of fossil and nuclear fuels – is uneven around the world, and this has significant implications for the energy security of many nations (Appendix C). Once available, though, fuels are convenient stores of readily-accessible energy, which can be traded, transported, and used to provide heat directly whenever desired. Fuels can also be used to provide work, but only indirectly through the use of a heat engine (an engine that converts heat input into work output via a cyclic process). As shown previously in Section 2.2, the efficiency of this conversion is thermodynamically constrained by the temperature difference between the process and its environment. In UK households, however, fossil fuels (and, to a much lesser extent, biomass fuels) are used mainly for the direct provision of heat in various forms; for space heating, water heating and cooking (this is covered in more detail in Chapter 4).

Electricity, in contrast to fuels, is a process that occurs simultaneously and instantaneously throughout an entire interconnected circuit (Patterson 2007b). Its geographic origins are less constrained; it can be generated almost anywhere with a wide array of different technologies and over a huge range of scales. At a national level, since it is not yet stored in large quantities<sup>4</sup>, it must be generated more or less exactly when it is used. The whole system is thus operating in real-time and stability must be ensured, instantaneously and continuously, via a complex balancing act of generally-controllable supply and generally-uncontrollable demand. Electricity has a high thermodynamic quality – a quality of one – and it can be readily converted into work (Section 2.4.3). In thermodynamic terms it is therefore sensible to use it only for high-quality applications (e.g. mechanical drives), but it is nevertheless used to provide all household end-uses including low-grade heating. There are a variety of reasons for this situation emanating at different points throughout the long development of the UK's electricity system. At times, for example, electrical heating has been encouraged to provide more consistent load (Section 3.4.2). Furthermore, the capital cost of electrical heaters is currently lower than that of fuel-based boilers, they take up relatively little space, and they operate quietly and cleanly at the point of use. They are sometimes attractive options for the end-user for these reasons, although running costs are relatively high since the unit cost of electricity is generally higher than other commercial energy carriers (e.g. gas).

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<sup>4</sup> Electricity is not yet stored on a large scale due to technical and economic constraints. 'Pumped storage hydro-electric' stations are one large-scale storage option that uses electricity to pump water to a high level reservoir, which is later released to generate electricity at peak times. But they are not used widely. In the UK, for example, they stored only 1% of the total electricity supply during 2005–2007 (4–5 GWh per year; BERR 2008a)

Electricity is first and foremost a function of infrastructure (Patterson 2007a); it can be generated without fuel, but not without infrastructure. This has led Patterson (2007a) to argue that the latter should be focused upon rather than only the units of electricity delivered over time, in particular when generation costs are presented in such terms. He argues that policy should be developed explicitly to alter the electricity infrastructure – the generators, the network, and the loads, but especially the loads and in particular buildings – to increase the reliability of the services the infrastructure delivers, to improve its performance, and to broaden its benefits (Patterson 2007a). Such considerations are beyond the scope of this chapter, since it is focused upon the supply system, but they are worth remembering during the course of this and subsequent sections.

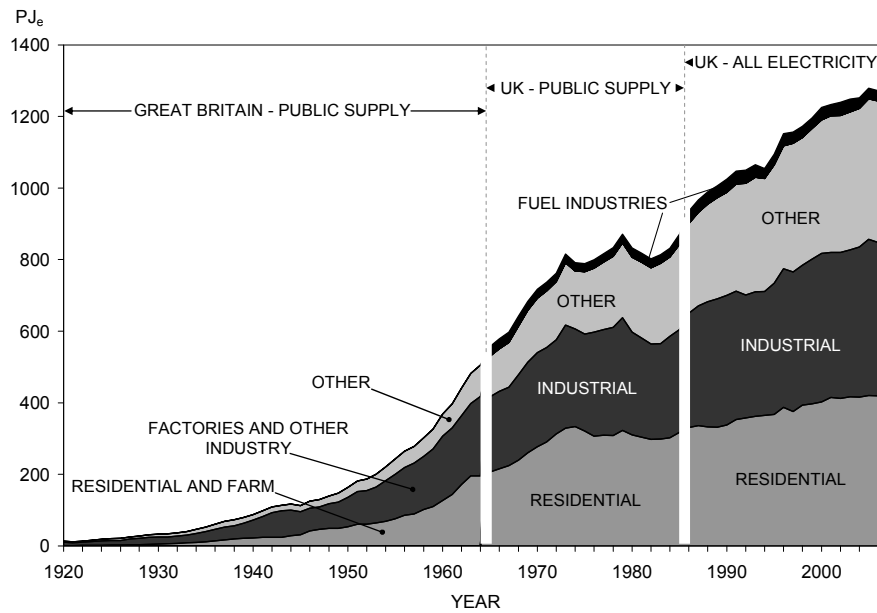
Although electricity can be generated and indeed supplied in many different ways, the predominant method around the world, which dates back more than a century, involves relatively few, large, remotely-sited power stations using rotating machines to generate synchronised, AC electricity (Patterson 2007b). These generators supply a high-voltage transmission network that feeds power in one direction – down through distribution networks at lower voltage stages to a large number of end-users. End-users can be connected to the grid at different voltage stages depending on their demand, but in terms of customer numbers, the largest category is low-voltage end-users such as households.

Britain has exactly this sort of ‘many loads, few sources’ electricity network (Burt et al. 2008), and the majority of the ‘few’ centralised generators are dependent upon fossil fuels. While this made sense during much of the network’s long development it is less justifiable now (Patterson 2007b). During its development, the conversion efficiency of fuel to electricity at the point of generation was focused upon, encouraging the use of larger and larger power stations. However, this process wastes approximately two-thirds of the fuel input as low-quality heat to the biosphere while, downstream, three-quarters of the residential sector’s energy demand is for precisely this sort of low-quality heat (Section 4.2). Looking from the perspective of the whole energy system this is thermodynamically wasteful; it could be far more efficient to generate nearer the loads, which also have heat loads, and to use the waste heat through combined heat and power (CHP) generators. There are a variety of drivers and constraints affecting the development of the electricity system, but it is likely that over the next few decades the UK will see a significant penetration of smaller-scale generation, energy storage, and controllable load – that is, a more highly distributed power system based upon the premise ‘many loads, many sources’ (Burt et al. 2008). This is important context for the research underlying this thesis, which investigates the thermodynamic performance of a variety of household-scale micro-generators. To give context to these analyses, further discussion of the current established electricity supply system, including a brief historical overview, is necessary.

### 3.4.2 A short history of electricity supply in the UK

In the 1860s, more than 30 years after Faraday announced his discovery of electromagnetic induction in 1831, electricity generators began to be produced enabling the commercial supply of electricity. In 1881 the town of Godalming, Surrey, was the first to receive a commercial supply, in this case in the form of combined public and private lighting. A range of public and private organisations subsequently developed generation capacity (DTI 2002a). As the industry developed in the 1920s, the Government came under pressure to establish a high-voltage transmission network to enable electricity to be generated in the most efficient stations of the time and then delivered, after stepping down the voltage during distribution, to wherever it was wanted. The Electricity (Supply) Act of 1926 started this process, and by the end of 1935 all of Britain except north east England was connected in one way or another (*ibid*). In 1945 the delivery voltage level became standardised at 240V AC, and standardisation of the grid frequency, at 50 Hz AC, was completely in 1947. In 1948 the British Government nationalised the whole electricity supply industry, and 1957 saw the establishment of the Central Electricity Generating Board (CEGB) in England and Wales, which superseded the British Electricity Authority. The CEGB took responsibility for both the generation of electricity in bulk and its transmission through the nationwide 'National Grid' to a number of 'bulk supply points'; 12 in England and Wales at that time (*ibid*). The Electricity Act of 1989 subsequently introduced competition into the industry as of 1<sup>st</sup> April 1990, and since May 1999 Great Britain has been fully competitive with all consumers able to choose their supply company (DTI 2002a). The various grid systems around the UK became linked in early 2002; two high-voltage lines connect Scotland to England and Wales with a total capacity of 2.2 GW since 2003, and a 500 MW connector joined Scotland to Northern Ireland in 2001. There is also a link between the Irish Republic and Northern Ireland (600 MW in 2001). In 1986 a connection to Europe, through France, was established, with a capacity of 2 GW that replaced an earlier 1960s 160 MW link (*ibid*).

These various and significant structural changes in the industry have affected the availability of long-term statistics, some of which are summarised below in both Figure 3-6 and Figure 3-7. Before 1951 the data covers public supply in Great Britain, and from this time onwards limited statistics have been available for generation and use in Northern Ireland and for generation by companies for their own use ('autogeneration'). Detailed statistics for the whole of the UK have been available since 1987.

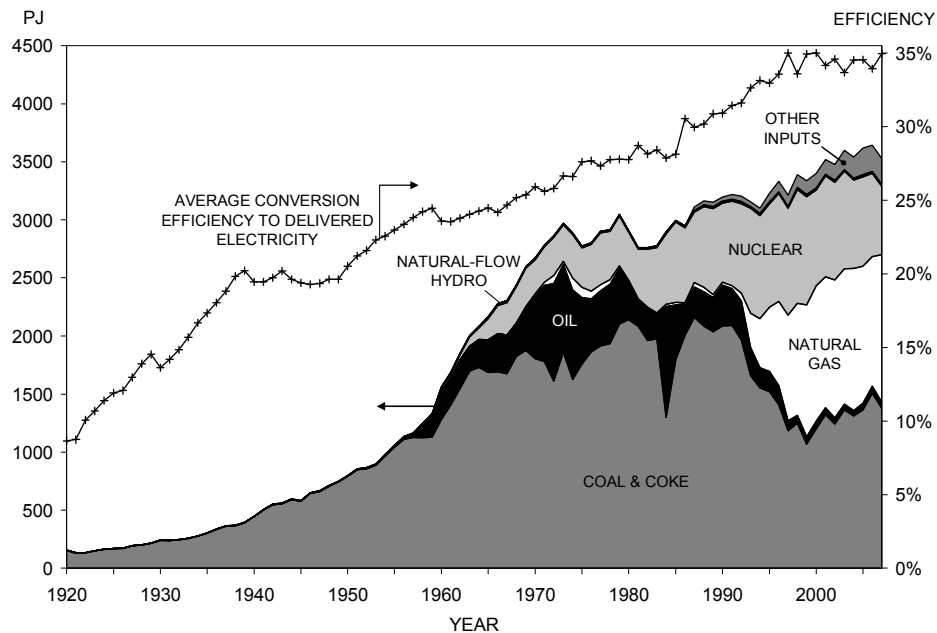


**Figure 3-6: Annual electricity use in Great Britain and the UK by sector, 1920–2007**  
(Source: BERR 2008h)

*Figure notes*

- 'Other' is shops, offices, commercial premises, public lighting, and traction until 1951, after which time it becomes public administration, transport, agricultural and commercial sectors.

Because electricity was originally used to power only public and private lighting, many power stations only operated between dusk and 11pm. In the 1890s it was realised that generation efficiencies were increased by more constant loads, and since early-morning and night-time electrical loads were higher due to lighting loads, generators promoted the use of electrical heating (a relatively large load) during the day to achieve a more consistent overall load (DTI 2002a). They even went so far as renting out electrical cookers and kettles with preferential charges for such uses; the forerunner to modern differential 'peak' and 'off-peak' pricing (*ibid*). Tramways, which replaced horse-drawn traction, were the next major source of demand after lighting, and then electric-arc steel-making became the biggest load during the First World War (*ibid*) prompting subsequent growth in industrial and commercial uses (Figure 3-6). More recently, since night-time loads were below day-time loads, residential night storage heaters were encouraged to increase night-time load through a differential pricing scheme – the 'Economy Seven' tariff (Strbac 2008). Figure 3-6 shows that the residential sector's annual electricity use grew rapidly in the 1960s and early 1970s, decreased in the wake of the 1973 and 1979 oil price 'shocks', and levelled until the mid 1980s, before growing again during the 1990s and then approximately levelling from 2000–2007. The estimated end-uses of this electricity within the residential sector, from 1970 onwards, are discussed in detail in Section 4.5.



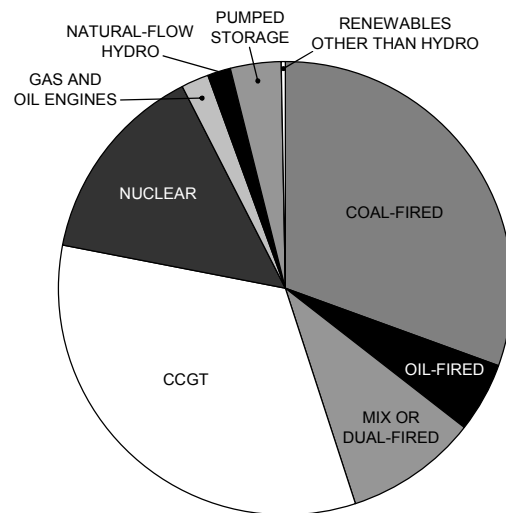
**Figure 3-7: British and UK electricity supply 1920–2007: primary inputs for electricity provision (left axis), and average conversion efficiency of inputs to delivered electricity (right axis)**  
(Source: BERR 2008h)

*Figure notes*

- Fuels inputs are in GCV terms
- 'Coal and coke' is in fact almost entirely coal; coke and breeze were used during the 1930s to early 1980s, but in relatively small proportion.
- The energy value for 'nuclear' is the enthalpy change of the working fluid by nuclear fission.
- The energy value for 'natural-flow hydro' is the energy content of the electricity produced by the hydro power plant, rather than the energy available in the water driving the turbines. A similar approach is adopted for wind turbines (which appear within 'other inputs').
- 'Other inputs' include coke-oven gas, blast furnace gas, waste products from chemical processes, refuse-derived fuels and renewable sources including wind.
- 'Natural gas' includes colliery methane from 1987 onwards
- Data for all generating companies are only available from 1987 onwards, and the figures for 1987 to 1989 include a high degree of estimation. Before 1987 the data are for major power producers, transport undertakings and industrial hydro and nuclear stations only.
- The approximate 'average conversion efficiency' was calculated by comparing the energy content of the inputs to the electricity system to the delivered electricity reaching the end-users, and hence includes electricity industry use along with transmission and distribution losses. Note that different generation technologies deviate from this overall annual average value.

Although the first commercial-scale supply of electricity came from hydro-power generators (DTI 2002a), the supply of electricity to meet the various demands has been achieved primarily on the basis of fossil and, since the early 1960s, commercial-scale nuclear fuel use (Figure 3-7). Some natural gas was used during the 1970s, but between 1975 and 1990 an EC Directive limited the use of gas in public power stations (DTI 2002a). The end of this limitation coincided with privatisation of electricity supply in the UK, and the 'dash for gas' (Hammond and Stapleton 2001) began with the commissioning of the first combined cycle gas turbine CCGT in 1992 (DTI 2002a). Since that time almost all new power stations have been CCGTs, and by 2007 they accounted for more than 30% of total

capacity (Figure 3-8). Since 1987 all generators have been included in statistics, and Figure 3-7 shows that 'other fuels' have shown significant growth. Major contributors to this category include coke oven gas and blast furnace gas (used for generation in the iron and steel industry) and more recently landfill gas and wind power. Though renewables (and landfill gas) have recently begun to make a contribution, Figure 3-7 shows clearly that the electricity system is based overwhelmingly on the use of fossil fuels, which constituted 79% of the primary input in 2007 (nuclear making up the majority of the remainder).



**Figure 3-8: Generating capacity of major power producers in the UK, 2007**

(Source: BERR 2008a)

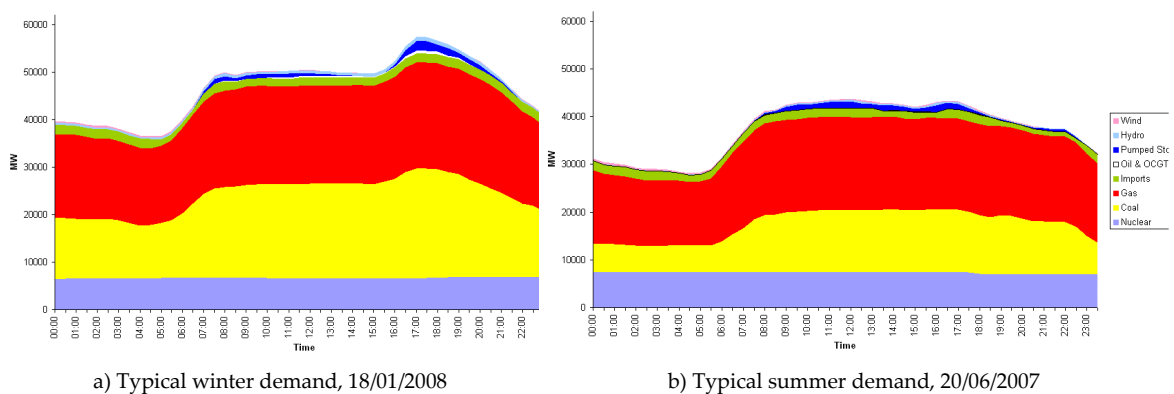
The total power generating capacity of major power producers<sup>5</sup> in the UK grew from 0.044 GW in 1892 to over 75 GW at the end of 2007 (Figure 3-8), at which point 'other generators' totalled 7.8 GW and included 1 GW of wind capacity; the largest renewable capacity other than hydro (BERR 2008a). The average size of generating plants grew significantly during the 20<sup>th</sup> century. The mean size of station was 6.5 MW in 1922, which grew to 458 MW by 1989 (DTI 2002a). The new CCGTs are typically smaller than the other large stations of the 1960s to 1980s. In 2001 the median size of coal-fired, nuclear, oil-fired, and CCGT plants were 1,930 MW, 1,150 MW, 520 MW, and 680 MW respectively (*ibid*).

<sup>5</sup> 'Major power producers' refers to the former nationalised industries, whereas 'other generators' refers to autogenerators – companies whose main business is not electricity generation but who generate for their own use – and new independent companies set up to generate electricity.

### 3.4.3 Meeting instantaneous demand

As previously indicated, the consideration of aggregated annual values can be particularly simplistic in the case of electricity. The stability of the UK grid currently relies upon an instantaneous balance between generally-controllable generation and generally-uncontrollable load (supply and demand), and sufficient supply is required to meet the maximum demand. The total instantaneous load varies significantly during the day and by season; from a maximum of just over 60 GW (a winter early-evening) to a minimum of approximately 23 GW (a summer night-time) during 2007/2008 (National Grid plc 2008). In 1962 capacity failed to meet demand, but since then power-station building has ensured a significant excess capacity compared to the maximum demand ('plant margin'). The margin exceeded 50% in 1973, but more recently has been in the range 20–25 % (DTI 2002a) and in 2007 it was approximately 28% (BERR 2008a).

The different plants used during 2007/2008 to meet the loads on typical winter and summer days are shown in Figure 3-9. Fossil-fuel plants form the clear majority and are, to differing extents, relatively flexible within a short timescale and thus do the majority of the load-following. Coal and gas stations are the main generators altering their overall output to follow the load, while pumped storage appears to be the main mechanism for finely tuning the overall generation (e.g. 5–5:30pm on Figure 3-9a). Nuclear, in contrast, is 'base-load' and is always on, while wind (a minority contributor at present) is an example of relatively uncontrollable generation, since it depends upon a variable ambient energy source. One (National Grid) projection of overall wind farm capacity growth is from 3.8 GW in 2008/2009 to 15.9 GW by 2014/2015, and National Grid foresees a large portfolio of such uncontrollable generation as manageable, providing flexible generation and other balancing services remain available (National Grid plc 2008).



**Figure 3-9: Generation mix to meet typical GB winter and summer demands, 2007/2008**  
(Reproduced with permission from National Grid plc 2008)

Although the loads are generally uncontrollable at present, there is much interest in increased application of controllable load and demand-side management (of which night-storage heating is an example) to alter this situation (see, for example, Burt et al. 2008 and associated publications). This could facilitate the integration of an increasing proportion of uncontrollable generation, since balancing could be achieved with an increasing amount of demand-side adaptation.



### 3.4.4 Average energy and exergy efficiencies for centralised electricity generators

The annual average (First Law) conversion efficiencies of coal, nuclear and CCGTs were 36%, 39% and 49% respectively in 2007 (BERR 2008a). Since exergy inputs are similar to energy inputs, and exergy outputs similar to exergy outputs (e.g. Table 2-3), the exergy efficiencies of these power plants is similar to their energy efficiencies. Szargut et al. (1988, in Hammond and Stapleton 2001) presented conversion factors to enable calculation of exergy efficiencies from energy efficiencies for a variety of large power plant, and these are summarised in Table 3-2.

**Table 3-2: Energy and exergy efficiencies for electricity generation**

Power plant type	Energy efficiency <sup>a</sup> ( $\eta$ ; 2007)	Energy-exergy efficiency relations <sup>b</sup>	Exergy efficiency ( $\psi$ ; 2007)
Conventional steam	36%	$\psi = 0.96\eta$	35%
Nuclear	39%	$\psi = \eta$	39%
CCGT	49%	$\psi = 0.96\eta$	47%

Source: a) BERR 2008a, b) Szargut et al. 1988 (in Hammond and Stapleton 2001)

Table 3-2 shows that the energy and exergy efficiency of electricity generation is below 50% in all cases, and hence more than 50% of the energy and exergy input is lost or destroyed. Although the energy and exergy efficiencies are similar, the underlying causes for their magnitudes are different. Section 2.2.2 showed that while the majority of the energy losses are as low-temperature waste heat, Reistad (1975) found that the majority (over 70%) of the exergy destruction in coal-fired power plants (conventional steam) was during combustion and heat exchange between the combustion products and the working fluid (see Sections 2.2.2 and 2.4.5).

Since energy and exergy efficiencies are similar, the exergy requirement of the electricity delivered to homes will be similar to the energy requirement for electricity; the ERE, which is presented below. And like natural gas, the overall exergy performance of electricity supply and use within homes will depend upon its final application. It can be anticipated that when electricity is used for low-quality space or water heating the overall exergetic performance will be poor. This is revisited in Section 4.7.

### 3.4.5 The average ERE of electricity

Similar to the case of natural gas, a pseudo *Energy requirement for energy* (ERE) for electricity may be approximated from national statistics (BERR 2008a); again these do not include life-cycle energy requirements of the supply system nor upstream requirements for primary imports. Statistics are summarised for 2007 in Table 3-3, which also presents data for 2005.

Table 3-3 indicates that in 2007 energy industry use was 8.0% of the electricity generated (3.3% of the primary energy input), while losses between generation and loads were 6.6% of the electricity generated (2.7% of the primary energy input). BERR (2008a) estimated that 22.3 PJ<sub>e</sub> of these losses (1.5% of the electricity generated or 0.6% of the primary energy input) were lost in the high-voltage transmission system and 68.4 PJ<sub>e</sub> (4.8% of electricity available or 1.9% of the primary energy input) were lost between the grid supply points (the gateways to the public supply system's distribution network) and

customers' meters (BERR 2008a). The unallocated remainder of the losses were attributed to theft and meter fraud.

**Table 3-3: From the electricity generator to the load, 2007**

Electricity industry information	Electricity (PJ)	
	2005	2007
Primary energy input (GCV) for electricity generation	3620	3530
Total electricity generated	1460	1440
Energy industry use, of which:	108	115
Electricity generation	(64.3)	(65.1)
Oil and gas extraction	(1.82)	(2.02)
Petroleum refineries	(16.1)	(16.8)
Coal extraction and coke manufacture	(4.19)	(3.86)
Blast furnaces	(1.85)	(1.72)
Pumped storage	(13.34)	(18.3)
Other	(6.77)	(6.77)
Losses, accruing from:	99.6	95.0
Transmission system	Unknown	(22.3)
Distribution system	Unknown	(68.4)
Unallocated	Unknown	(4.30)
Final delivered electricity, of which:	1250	1230
Residential sector demand	421	414
Pseudo-ERE of delivered electricity	2.90	2.87

(Source: Adapted from BERR 2008a Table 5.1 and paragraph 5.66 of both DTI 2006a and BERR 2008a)

The approximate 'pseudo-ERE' of delivered electricity was calculated by dividing the total 'primary energy' input by the total delivered electricity, and Table 3-3 shows that this value is approximately 2.9 for both 2005 and 2007. Put another way, approximately 35% of the primary energy (in GCV terms) entering the electricity supply system was delivered as electricity to the end-user. This annual average conversion efficiency of primary energy inputs to delivered electricity is presented on Figure 3-7 (p.47) for the period since 1920. It has risen from 9% in 1920 to approximately 34–35% since the late 1990s (on a GCV basis). The majority of the losses are due to the conversion of fuel inputs to electricity outputs within thermal power stations, whose waste heat is emitted at the bottom-end of their power cycles. In 2007, for example, approximately 59% of the total 65% primary energy losses occurred during the conversion stage (the remaining 6% were energy industry use and transmission/distribution losses).

The combustible fuel components of the primary energy input shown in Table 3-3, which constitute approximately 83% of the total primary input (nuclear making up the majority of the remainder), are presented in gross calorific value (GCV) terms; the convention for UK energy statistics. BERR now also publish, online, the overall 'Energy Balance' tables in net calorific value (NCV) terms; see BERR 2008c. For both 2005 and 2007 the primary energy input in NCV terms was 94% of the primary energy input in GCV terms, and an average pseudo-ERE for electricity based on NCV measurements would therefore be 2.72 in 2005 and 2.70 in 2007. In this case 37% of the primary energy input in NCV terms ends up as electricity for the end-user.

During collaborative work with M. McManus, a researcher carrying out a life-cycle assessment (LCA) of the micro-wind turbine discussed in Chapter 5, full EREs for

electricity from a variety of sources were estimated in NCV terms (Allen et al. 2008b). They are replicated in Table 3-4, and were produced in a similar manner to that outlined for natural gas at the end of Section 3.3.2. The fuel-mix of 2005 was used to estimate the ERE of an average unit of delivered electricity in the UK.

**Table 3-4: Energy requirement for energy (ERE) of electricity generation technologies, in NCV terms**

Electricity generation technology	ERE $\left(\frac{\text{MJ}_{\text{resource}}}{\text{MJ}_{\text{delivered}}}\right)$	Comments
UK grid, 2005 <sup>a,b</sup>	3.1	Representative of the 2005 UK electricity system.
Coal <sup>b</sup>	3.5	Representative of electricity production from coal in UCPTE countries.
Natural Gas <sup>b</sup>	2.3	Based on average of natural gas power plants in Great Britain.
Oil <sup>b</sup>	4.6	Based on UK specific efficiency of transformation. Assumed mix of 35% combined cycle plants (1.9TWh), 65% from power plants (3.6TWh).
Nuclear <sup>b,*</sup>	3.5	Represents the average European nuclear mix of 90% Pressurised Water Reactors and 10% Boiling Water Reactors (values based on electricity delivered 1995 – 1999).
Hydro <sup>b</sup>	0.01	Based on the UK share of run-of-river and reservoir hydro schemes.
Wind (2MW offshore) <sup>b</sup>	0.06	Based on a capacity factor of 30%.
Wind (800kW onshore) <sup>b</sup>	0.05	Based on a capacity factor of 20%. Values may therefore be conservative; the average UK capacity factor (1998 to 2004) was 29% (DTI 2006c).
Solar (3kW <sub>p</sub> roof mounted) <sup>b</sup>	0.34	Values may be optimistic. They are based on the solar resource available in Switzerland, which is approximately 1300 – 1600 kWh/m <sup>2</sup> , compared to the UK’s resource of 900 – 1300 kWh/m <sup>2</sup> (Suri et al. 2007).

Source: a) Adapted from DTI (2006a); b) Adapted from Swiss Centre for Life Cycle Inventories (2007)

\* Note that the spent fuel of a nuclear reactor may contain, with reprocessing, utilisable energy

Table 3-4 indicates that the ERE of an average unit of UK electricity during 2005 was approximately 3.1, which means that 3.1 of energy resource (in NCV terms) have been used, on average, for every unit of delivered electricity. This value is notably larger than the pseudo-ERE (NCV) of 2.7 calculated above, which implies that a considerable amount of energy is used in stages that are excluded from the annual DUKES statistics (Table 3-3).

Having noted the difference between the pseudo-ERE and the complete ERE, it is clear that the dominant factor in the ERE's of thermal power plant (and thus the 2005 grid, since it is based primarily on thermal power plant) is the operational conversion efficiency of input fuels to electricity. The first two rows of Table 3-3 indicate that 2.5 units of primary energy are required for each unit of generated electricity, which is the clear majority (81%) of the complete ERE that incorporates all life-cycle requirements, upstream energy requirements for fuels, and downstream transmission and distribution losses.

Table 3-4 shows that the EREs of electricity from ambient renewables (plus reservoir hydro) are much smaller than those of the thermal power plants. This is primarily because the latter are based upon the conversion of heat, released from fuels, into electricity via a heat engine, which entails a large low-grade heat loss. Since the input fuels are within the system boundary (Section 2.3.3), and their energy content is included in the ERE calculation (total requirement per unit of delivered electricity). The ambient renewables, in contrast, generate electricity from ‘free’ energy inputs; inputs that are outside the system boundary and hence not included in the ‘requirements’ account.

The ERE figures presented thus far are *descriptive* rather than *prescriptive*; they describe the energy consequences of fuel and electricity use (within the scope of the defined system boundary), but they do not incorporate a value judgement nor tell the analyst which option *ought* to be used. It is, however, often difficult to separate descriptive statements from prescriptive statements; since many statements that are formally of one type carry implications of the other (Dictionary of Economics 2009b). Care must therefore be taken when interpreting the numbers and drawing conclusions for decision-making purposes. There are many other economic, political, technical and other factors that influence the development and use of energy systems. Technical constraints, for example, include geographical suitability, flexibility of plant, capacity credit, and ancillary services offered (Allen et al. 2008b). The net energy figures presented above should therefore be taken as one input to a wider decision-making process regarding the electricity system.

#### 3.4.6 The marginal ERE and associated carbon emissions factor of electricity

Figure 3-9 (p.49) shows that at any given moment the electricity being delivered to end-users is derived from a mixture of different types of generator. This mix varies continually and so too, therefore, does the energy-resource use (e.g. combustion of fossil fuel) and emission of carbon dioxide associated with each unit of delivered electricity. It is impractical if not impossible to allocate exact, instantaneous upstream energy use and carbon emissions to either individual electricity demands or changes in those demands. Two fundamentally different compromises have been proposed in response to this – the *system-average* approach and the *marginal-plant* approach, depending on the situation.

The *system-average* approach takes historic, usually annual, data to calculate the average energy requirement (ERE), or carbon emissions associated with, a unit of electricity. This was how the average EREs were calculated in the previous section and it was also how Figure 3-4 (carbon emissions allocated to different sectors) was produced. DEFRA adopts this approach to enable businesses to calculate their (historic) carbon emissions when producing environmental reports (DEFRA 2008b). In such situations it is generally impossible to align particular end-users with particular types of electricity generation in any meaningful way, and the use of annual-average factors therefore appears to be the only practicable approach (Bettle et al. 2006). DEFRA gives a five-year rolling average because year-to-year changes can be quite large, and this value was 0.537 kgCO<sub>2eq</sub>/kWh in the available guidelines at the time of writing (DEFRA 2008b).

The *marginal-plant* approach applies when estimating the marginal effect of a change in electricity demand, although the system-average has also been used previously for this purpose (Hitchin and Pout 2002). Not all power stations are affected equally when demand for electricity changes: the operation of 'base-load' (e.g. nuclear) or less controllable (e.g. wind turbine) stations is likely to be unchanged while *marginal* plants adjust their output (Carbon Trust 2007). This can be seen on Figure 3-9, where coal and gas fired generation (in particular) vary their output throughout the day in response to changing demand. When demand for electricity from the established grid is reduced, for example by installing energy-efficient light-bulbs or alternative generators such as solar photovoltaic arrays, marginal plant will reduce their output accordingly; a direct, short-term effect on existing plants (Hitchin and Pout 2002). In the longer-term, such changes in demand, if lasting, will ultimately affect the evolution of the power system; an indirect, longer-term effect on future plants (Voorspools and D'haeseleer 2000; Hitchin and Pout 2002). Both direct and indirect effects will vary depending on the magnitude and temporal characteristics of the demand changes.

This thesis considers, in later chapters, the upstream energy-resource and carbon emission saving enabled through a marginal reduction in demand caused by electricity micro-generators. It is seen below that the marginal ERE and carbon-emission factors are significantly different to system-average values, and hence it is necessary to use a marginal ERE or carbon-emissions factor rather than the system-average values.

While it is relatively simple to qualitatively describe the possible direct and indirect effects of marginal demand changes, it is by no means easy to quantify them (Hitchin and Pout 2002). Before deregulation of the electricity market, the Central Electricity Generating Board would determine which plant operated according to the demand at the time, and it was therefore easier to predict which existing marginal generation would be displaced in the short term given a reduction in demand from a specified point (Carbon Trust 2005). In the current deregulated market, however, the short-term marginal plant depends upon a complex mix of local and global economic factors. In recent years, for example, coal has often been favoured over gas for reasons including the remaining economic life of the plant, the expected future cost of carbon, and the relative prices of coal and gas (*ibid*).

Nevertheless, Bettle et al. (2006) estimated direct marginal carbon emissions factors out to 2020, for reductions of 0.5–5% of annual electricity demand (via certain demand-reduction measures such as the removal of night-storage heaters or certain types of lighting). To do this they modelled the electricity system on the basis of (historic) half-hourly generation data, fuel-use of different plants, typical generation efficiencies, emissions factors for different generator-types, and UK Government energy-use projections (DTI 2000). Bettle et al. found that, for the specific variety of electricity end-uses that they modelled, the direct marginal emissions factor was generally around 50% higher than the system-average emissions factor. They were unable to develop general rules for emissions factors for different end-uses and scales of reduction because the results depend upon the specific demand changes assumed, and thus they proposed a pragmatic approach of simple factors for the purposes of initial estimations by other researchers. They proposed

0.661 kgCO<sub>2eq</sub>/kWh for 2005, 0.503 kgCO<sub>2eq</sub>/kWh from 2010, and 0.448 kgCO<sub>2eq</sub>/kWh in 2020. These figures did not include transmission and distribution losses, which would increase the emissions factors, nor did they include any indirect long-term effects of demand reduction. The values are based upon the 'CL' (central GDP growth, high fuel prices) and 'CH' (central GDP growth, low fuel prices) annual generation-mix scenarios of the DTI (2000). These generation-mix scenarios are shown in Table 3-5, alongside the generation mix of 2005 from DUKES (DTI 2006a). Comparison shows that the most significant shift that is expected by the scenarios is a move away from coal and towards the use of gas (nuclear also reduces and renewables increase).

**Table 3-5: Electricity generation mixes in 2005 and 2020**

Electricity generation by fuel-type (output basis)	2005 <sup>a</sup>	CL 2020 <sup>b</sup>	CH 2020 <sup>b</sup>
Coal	34%	6%	13%
Oil	1%	0%	0%
Gas	39%	75%	68%
Nuclear	20%	7%	7%
Renewables	4%	11%	11%
Imports	2%	1%	2%

Source: a) DTI 2006a; b) DTI 2000

For comparison with Bettle et al.'s figures, the Carbon Trust used a marginal emissions factor of 0.568 kgCO<sub>2eq</sub>/kWh during their recent modelling of the carbon saving potential of micro-CHP (Carbon Trust 2007). It is unclear whether or not this includes any indirect (long-term) considerations, since this is unstated in its source (the 2005 version of the UK Government's 'Standard Assessment Procedure for Energy Rating of Buildings'; BRE 2005b). Given DEFRA's much lower indirect value (outlined in the following paragraph), however, this seems unlikely. In comparison to the value of 0.568 kgCO<sub>2eq</sub>/kWh, Rankine et al. (2006) point out that some studies have assumed that coal-fired generators would be the marginal displaced plant, and have therefore employed a significantly higher carbon emissions factors of approximately 0.9 kgCO<sub>2eq</sub>/kWh.

In stark contrast to these direct (short-term) emissions factors, many organisations and individuals have used a value of 0.430 kgCO<sub>2eq</sub>/kWh in accordance with DEFRA's Environmental Reporting Guidelines (Carbon Trust 2007 and see, for example, Peacock and Newborough 2005; Hawkes and Leach 2008; Peacock et al. 2008). DEFRA's guidelines state that the value should be used 'when appraising policies that reduce electricity consumption or encourage the use of renewable electricity' (DEFRA 2008b). It is an exclusively indirect (long-term) emissions factor with no direct-effect considerations; it corresponds to plants that will not be constructed in the future due to the demand reduction expected to be induced by the policy. The value represents current combined-cycle gas turbine technology.

Two main comments can be made regarding the foregoing discussion. First, that the direct marginal carbon-emission factor for electricity is notably higher than that of the system-average emissions factor (Bettle et al. 2006). In the absence of a combined direct and indirect factor, the 'direct' values are considered here to be more representative of the effect of installing a micro-generator. The fact that the Carbon Trust apparently took this

approach in their recent micro-CHP study (Carbon Trust 2007), on the basis of the Government's 'Standard Assessment Procedure for Energy Rating of Buildings', lends weight to this approach. The second comment that may be made regarding the foregoing discussion is that direct marginal emissions factors are expected to reduce out into the future (system-average factors would also therefore reduce), on the basis of a projected move away from the use of carbon-intensive fossil fuels. Such projections are, however, only informed estimates and hence should be viewed as imprecise.

To summarise so far, there is considerable uncertainty regarding estimations of the energy-resource requirement and carbon emissions associated with electricity use; particularly in the case of estimating the marginal effect of a change in electricity demand such as through adoption of an electricity micro-generator. Focusing upon marginal carbon emissions factors rather than marginal energy use (since there is more recent published data for the former), the highest emissions factors that have been proposed are more than double the lowest values;  $\sim 0.9 \text{ kgCO}_2/\text{kWh}$  compared to  $0.43 \text{ kgCO}_{2\text{eq}}/\text{kWh}$ . This clearly has a significant effect on the calculation of the carbon savings enabled by a micro-generator (or demand-reduction measure). The evidence above suggests current direct marginal emissions factors are in the region  $0.57\text{--}0.71 \text{ kgCO}_{2\text{eq}}/\text{kWh}$  (the latter figure being an adjusted value from Bettle et al. 2006 to account for 7% transmission/distribution losses in accordance with Table 3-3), and that they will steadily decrease to something like  $0.48 \text{ kgCO}_{2\text{eq}}/\text{kWh}$  by 2020 (again, Bettle et al. 2006 et al. with transmission/distribution loss added). The majority of the decarbonisation is because coal is assumed to be increasingly replaced by gas. These figures give an overall range of  $0.71 \text{ kgCO}_{2\text{eq}}/\text{kWh}$  in 2005 to  $0.48 \text{ kgCO}_{2\text{eq}}/\text{kWh}$  in 2020; both of which being values estimated by Bettle et al. (2006). These have been selected as a reasonable range to use when assessing the carbon-emission savings enabled by a micro-generator in Chapters 5 and 6.

Unfortunately, since Bettle et al.'s direct marginal emissions factors are estimated via a complex modelling procedure, it is not directly possible to estimate the associated marginal energy requirement (marginal ERE) of electricity use. Furthermore, the emissions factors presented so far do not include any proportion of life-cycle emissions beyond the direct burning of fossil fuels (e.g. production of generators). To deal with these twin issues an approximation was made by the present author to estimate marginal EREs and emissions factors that do include other life-cycle stages of the marginal plants. This was done by assuming that the marginal carbon emissions factors constitute only coal and gas, as indicated by the Carbon Trust (2007) and by Figure 3-9 (which shows that coal and gas-fired plant do the majority of the load-following). Bettle et al. (2006) present a breakdown of the emissions factors used during their modelling. Taking 'large coal' and 'CCGT' from the values they list gives emissions factors of  $0.88$  and  $0.44 \text{ kgCO}_{2\text{eq}}/\text{kWh}$  for electricity from coal and gas respectively. Using these values and the stated assumption, it can be inferred that Bettle et al.'s maximum emissions factor ( $0.661 \text{ kgCO}_{2\text{eq}}/\text{kWh}$ ) comprises approximately 50% gas and 50% coal as the marginal plants. Similarly, their minimum value (of  $0.448 \text{ kgCO}_{2\text{eq}}/\text{kWh}$ ) comprises 98% gas and 2% coal as marginal plants. Using ERE values from Table 3-4, which incorporate transmission and distribution losses,

marginal EREs corresponding to these emissions factors were calculated as 2.9 and 2.3 units of energy resource used per unit of delivered electricity respectively.

The EcoInvent database (Swiss Centre for Life Cycle Inventories 2007), used to estimate the EREs of different electricity generator in Table 3-4, also provides carbon emissions factors for generators that include other life-cycle stages such as production of the generator. For coal, this emissions factor is 1.03 kgCO<sub>2eq</sub>/kWh while for gas it is 0.48 kgCO<sub>2eq</sub>/kWh (including transmission/distribution losses). Using the proportions of each generator type from the preceding paragraph, updated marginal emissions factors were estimated as 0.76 kgCO<sub>2eq</sub>/kWh for 2005 and 0.49 kgCO<sub>2eq</sub>/kWh for 2020. (Considering the uncertainties associated with the numbers, two significant figures is considered ample for these values.)

In conclusion, marginal EREs and carbon emissions factors associated with a reduction in electricity demand are approximations of a complex system. These approximations are typically presented as annual values that vary from year to year and are expected to decrease in the future. The estimation above suggests that the marginal carbon emissions factor was approximately 0.76 kgCO<sub>2eq</sub>/kWh for 2005 and could reduce to 0.49 kgCO<sub>2eq</sub>/kWh by 2020, if UK Government projections come to pass. These values consider the full life-cycles of generation plant, amortised as appropriate. The associated marginal EREs, calculated on the basis of the simplifying assumption outlined above, are 2.9 and 2.3 MJ<sub>resource</sub>/MJ<sub>delivered</sub> respectively. In both cases the figures assume the use of coal and gas as the marginal plants, with the future values constituting a greater proportion of gas in the mix. Future technology has been simplified as the technology of today, although clearly improvements may well be made and further decrease the future values. On the other hand, while predictions are for increasing gas-use and hence de-carbonising, increasingly primary-energy efficient electricity, it is possible that coal could remain in the marginal mix longer than projected and hence the figures would remain more like current values. For the purposes of this thesis, the values summarised in this paragraph are used to give a reasonable range to the calculations of the carbon and energy-resource 'savings' enabled by an electricity micro-generator. There are, however, many other pathways for electricity-system development than that considered above. It is therefore recommended that further work investigate other possible generation mixes and iterate the estimations presented here.

During earlier research involving the present author (Allen et al. 2008a and 2008b), estimates of energy-resource and carbon savings enabled by electricity micro-generators were based upon the system-average generation-mix for the UK in 2005. This entailed an ERE for grid electricity of 3.1 units of energy resource for each unit of delivered electricity and a system-average carbon emissions factor of 0.58 kgCO<sub>2eq</sub>/kWh. (A similar 'system-average' approach has been taken elsewhere in the micro-generation literature, such as Rankine et al. 2006, who used a system-average emissions factor of 0.46 kgCO<sub>2</sub>/kWh). The foregoing discussion, however, which is based upon more recent research by the present author, indicates that marginal values are more appropriate than system-average values.



Comparison between the values used by Allen et al. (2008a and 2008b) and those given in the previous paragraph leads to the following conclusions:

- The system-average ERE for electricity is greater than the marginal EREs. This is because the marginal value has a higher proportion of energy-efficient gas generation compared to the system-average value that includes more energy-inefficient nuclear (see Table 3-4). The 2005 and 2020 marginal EREs are 94% and 75% of the 2005 system-average ERE, respectively.
- The system-average carbon emissions is toward the middle of the marginal range outlined above; it is lower than the 2005 marginal emissions factor but higher than the 2020 marginal emissions factor. In the 2005 case, the difference is because coal is a bigger proportion of the marginal mix than in the system-average case, since the latter includes a proportion of low-carbon nuclear (and renewables to a lesser extent). In the 2020 case, it is because gas plays a significant role in the marginal emissions factor relative to the 2005 system average. The 2005 and 2020 marginal emissions factor is 131% and 84% of the 2005 system-average factor, respectively.

In conclusion, the energy-resource savings calculated by Allen et al. (2008b; 2008a) are larger than marginal EREs would suggest, while Allen et al.'s carbon savings are toward the middle of the marginal range. In Chapters 5 and 6, which update work presented by Allen et al., the range of marginal EREs and carbon emissions factors are used to update the energy-resource and carbon savings estimated by Allen et al..

### 3.5 SUMMARY

This chapter has given overviews of the main two energy supply systems utilised by UK households – the electricity and gas supply systems. An *Energy requirement for energy* (ERE) and *carbon-emission factor* have been estimated for delivered electricity and gas, as well as for (heating) oil. In Chapters 5 and 6 the values are multiplied by estimated electricity or fuel savings enabled by micro-generators, in order to estimate the overall energy-resource and carbon saving enabled by those micro-generators.

When a micro-generator causes a reduction in the use of the established energy supply systems it has a *marginal* effect on those systems. It has been assumed here, however, that average EREs and carbon-emission factors are sufficiently accurate for delivered fuels (gas and oil), in accordance with other contemporary literature. In contrast, it was concluded that average values are inappropriate in the case of electricity, because only certain *marginal* plant will be displaced by micro-generators. Accordingly, marginal EREs and carbon-emission factors have been estimated for reductions in electricity use.

## CHAPTER 4

# ENERGY USE IN UK HOUSEHOLDS

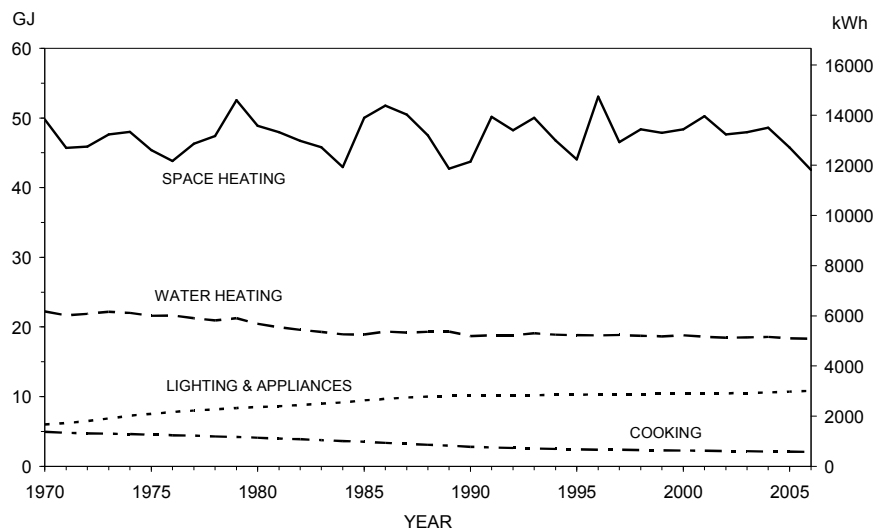
### 4.1 INTRODUCTION

There is great interest in micro-generation technologies for their ability to reduce the use of established energy resources – mainly fossil fuels – and hence reduce the carbon emissions of UK households. A perspective on the energy demand of households is therefore necessary when interpreting the performance of the micro-generators assessed in Chapters 5 and 6. In particular, it is useful to compare the estimated energy outputs of the micro-generators with representative household demands. This is electricity demand in the case of the micro-wind turbine and solar photovoltaic panel, and hot water demand in the case of the solar hot-water system. This chapter therefore presents an overview of the main uses of energy within households, with particular focus on representative electricity and hot water demands.

The calculation of representative household energy demands is by no means trivial. The mean average is a useful parameter, and easily calculated since aggregated data for the overall sector is the most readily available. Mean energy use does not, however, communicate variation within the housing stock. Since comprehensive samples of household energy-use data are generally lacking, it is often impossible to calculate parameters such as the standard deviation in order to describe variance. As a result, this chapter presents trends in the mean average and then, wherever possible, it indicates variation around the mean and/or alternative averages (e.g. the mode).

### 4.2 OVERVIEW OF ENERGY USE IN THE RESIDENTIAL SECTOR

Figure 4-1 shows how delivered energy is used within the (arithmetic mean) average UK household in terms of four end-use categories: space heating; water heating; cooking; and lighting and appliance-use. It shows that the clear majority of delivered energy is used for space heating, which represented 42.5 of the total 73.7 GJ/yr in 2006. Notwithstanding the fluctuations that are driven partly by external temperature variations (Utley and Shorrock 2008), this annual use has remained broadly constant over the period shown. Water heating requires the second largest quantity of delivered energy – 18.3 GJ/yr in 2006 – and Figure 4-1 indicates that this is a decrease of 18% from 1970 levels. Cooking, the smallest user of delivered energy at 2.1 GJ/yr in 2006, has also decreased since 1970, this time by a significant 58% from the 1970 level. The category ‘lights and appliances’ has shown by far the largest growth and was, at 10.8 GJ/yr in 2006, 180% of its 1970 level.

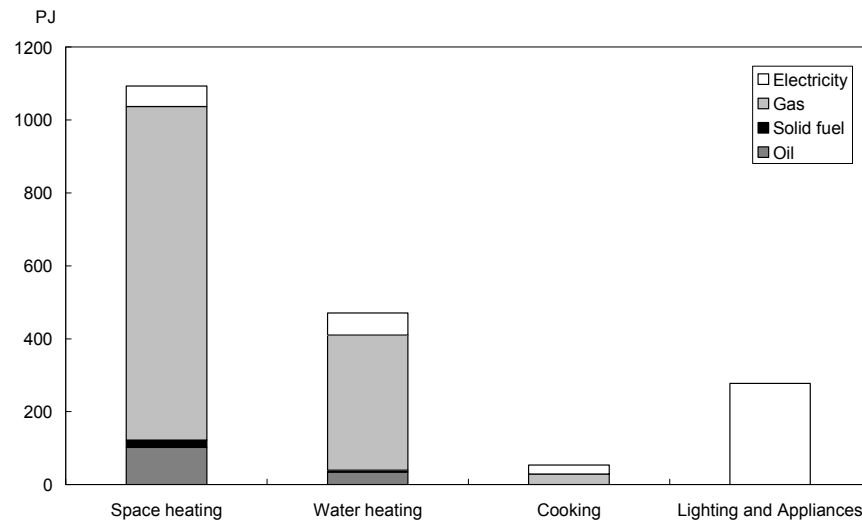


**Figure 4-1: Average UK household delivered-energy use by end use, 1970–2006**  
(Adapted from BERR 2008e)

Figure 4-1 is the average household of the overall residential sector data published by BERR (2008e). The BERR figures are based upon modelling by the Building Research Establishment, such as that reported by Utley and Shorrock (2008). The model used is 'BREHOMES', a physical model of the UK housing stock, in conjunction with 'BREDEM', a physical model of individual dwellings. A methodological description of these is given by Shorrock and Dunster (1997). They describe BREHOMES as a highly disaggregated model of the UK housing stock that is based upon statistical sources such as the English Housing Condition Survey (EHCS; e.g. DCLG 2008) and market research data on heating-systems and insulation. It focuses on the heat balance of the housing stock, and includes characteristics such as areas of dwelling elements (walls, roof, windows, etc) and their thermal characteristics (U-values), as well as data on heating system characteristics (fuel type and efficiency), internal temperatures and heating patterns, number of occupants, external temperatures and solar gains (Shorrock and Dunster 1997). These data are used in conjunction with the BREDEM model to provide a 'bottom-up' estimate of heating demand, which also includes a crude, floor-area based estimates of electricity use for lighting and appliances (e.g. BRE 2002). The fuel and electricity demand of the housing stock is thus estimated, and then calibrated against 'top-down' fuel and electricity use data from national energy statistics (DUKES; e.g. BERR 2008a). Shorrock and Dunster (1997) state that agreement is usually within a few per cent provided the various inputs have been entered correctly. Fine-tuning is carried out by adjusting the demand temperatures for centrally and non-centrally heated dwellings, usually by 0.1–0.2°C, from the original values that are based on spot temperature measured from the EHCS. The values given in Figure 4-1 are therefore indirect estimates rather than directly measured values.

Figure 4-2 shows the BREHOMES-derived breakdown of the energy carriers use to provide each end use, for the residential sector as a whole during 2006. It shows that the fossil fuels delivered to households are used to provide heat for either space heating, water heating or cooking (constituting 91% of the delivered energy used for these purposes),

while electricity is used for all end-uses and exclusively in the case of ‘lights and appliances’.



**Figure 4-2: Delivered-energy carriers used for each end-use in the residential sector, 2006**  
(Adapted from BERR 2008e)

Underlying and preceding the 2006 space- and water-heating breakdown of Figure 4-2 has been a notable trend towards central-heating systems for the provision of space heating; from 31% of dwellings in 1970 to 91% in 2006 (Utley and Shorrocks 2008). As implied by Figure 4-2, gas-fired systems have driven this trend. In the majority of cases (86% of the English housing stock; UK figures unavailable in this case), water heating is also provided by the central-heating boiler (Williams 2006), which explains the similar prevalence of gas for water heating.

Given this brief overview, this chapter now discusses space heating, water heating, and the variety of electricity end-uses. With the exception of space heating, which is included for context since it is a major element of household energy demand, the aim is to provide representative annual energy-demand values. The stage at which these demands are discussed varies, depending on data availability and the needs of the micro-generator chapters. The solar hot-water assessment in Chapter 6, for example, requires the estimation of the household's hot water demand. This is the *energy service*; a specified volume and temperature of hot water. In the case of the micro-wind and solar PV assessments of Chapters 5 and 6, it is the electricity demand (the *delivered energy*) that is of interest, since this gives context to the quantity of electricity provided by the micro-generators. Since it is not vital to trace electricity through to the energy services it ultimately provides, such an analysis is beyond the scope of this chapter. Following the discussion of annual energy demands, some examples of daily demand profiles are given before some complementary insights from exergy analysis are presented.

### 4.3 SPACE HEATING

#### 4.3.1 Factors affecting delivered energy demand

There are a wide variety of factors that affect the quantities and destinations of the fuel and electricity used within a household, and they can be categorised broadly as either technological or behavioural. Technological factors relate to the physical characteristics of end-user technologies and infrastructure, and include the conversion efficiencies of appliances; the insulation levels of and within the household; and the size (or power rating) of the appliances and household. Behavioural factors relate to the people living within the household and using the end-use appliances. They include desired temperature levels (e.g. of rooms or hot water); occupancy; lifestyles and patterns; and appliance choice and ownership.

In the case of space heating, behavioural factors include the householder's desired internal temperature; the use of heating timers and thermostats; and the time spent within the household. Technological factors include the conversion efficiency of the space-heating system; the external climate (which varies with geographical location and with season); and the building's physical characteristics such as insulation level, construction materials and size. The load placed on the space-heating system is invariably less than the total demand of the dwelling because 'free' heat is gained from appliances, lights, cookers, water-heating system components and natural sources such as solar insolation. Utley and Shorrocks (2008) estimated that in 2006 as much as half of the total space heating requirement was provided by such incidental gains.

#### 4.3.2 Trend of energy service demand

The energy service provided by a space-heating system is a desired internal temperature. This drives the space heating process, usually via a thermostat and control system in the case of a central-heating system. Internal-temperature and hence comfort levels have improved dramatically in recent decades, largely due to the dramatic increase in the penetration of central-heating systems (91% of households in 2006; Utley and Shorrocks 2008). Central-heating systems in the UK typically distribute heat around the home by circulating hot water from a centralised boiler around a system of radiators, and enable many rooms in a home to be heated by one boiler. This contrasts with non-central heating methods such as fireplaces or individual electrical room heaters, which provide localised heat. Utley and Shorrocks (2008) estimated that average internal temperatures in centrally-heated homes were 14°C in 1970 and 18°C in 2006, while in non-centrally heated homes they were 12°C in 1970 and 16°C in 2006. They suggest that average temperature will stabilise as more households move towards their desired comfort levels and that for most people 21°C is a 'comfortable' living room temperature while 2°C lower temperatures are adequate elsewhere in the home, giving an overall comfort level of perhaps 19–20°C. This is in line with World Health Organisation recommendations (in Boardman et al. 2005) of 21°C for the main living area and 18°C for the rest of the home.

Ideally, internal temperatures can be converted into a *base temperature* for a building (which is less than the internal temperature due to the existence of internal gains), and then

combined with external temperature data to communicate the space heating demand through the concept of *degree days* (see, for example, Layberry 2009). This is beyond the scope of the present discussion, however, since such space-heating energy service demands are not used later in this thesis during the micro-generator assessments.

#### 4.3.3 Trend of mean household delivered energy demand

Given the dramatic increase in temperature (and hence comfort) levels within households, the broad stability of delivered-energy use for space heating over recent decades (Figure 4-1) is impressive. Balancing the trend of increasing comfort levels have been increases in insulation levels and in the conversion efficiencies of heating systems. Indeed, Utley and Shorrock (2008) estimate that these efficiency measures have prevented a doubling in delivered-energy use.

Building regulations in 1965, 1976, 1982 and 1990 improved the thermal characteristics of new buildings and since 2002 have caused the majority to be built with filled cavity walls and double glazing (Utley and Shorrock 2008). However, while insulation measures across the overall housing stock appear to have saturated for at least loft insulation (one of the most cost-effective insulation methods), the proportion of households with *full insulation*<sup>6</sup> was still less than a fifth of all homes in 2006 (Utley and Shorrock 2008). There is thus great potential for improved insulation levels and hence decreased energy demands from space-heating systems.

The conversion efficiency of on-site fuel-based heating systems has improved significantly since 1970. Utley and Shorrock (2008) estimate that average central-heating efficiencies (fuel input to heater output) were 59% in 1970 compared to 76% in 2006, while non-central heating efficiencies have improved from 46% to 65% over the same period. The overall, weighted-average space-heating efficiency (taking into account the changing proportions of each heating system type) has improved from 49% to 74%. This trend of increasing conversion efficiencies can be expected to continue, since building regulations now stipulate that efficient boilers are installed. The UK's Central Heating System Specifications (CHeSS) set out the basic efficiency levels required by new boiler installations to meet building regulations, and at the time of writing these were last specified in 2005 (Energy Saving Trust 2005a; Energy Saving Trust 2005b). For a domestic central heating system with a 'regular' boiler and separate hot water store, for example, boilers must have a SEDBUK<sup>7</sup> efficiency of at least 86% in the case of gas, and 85% in the case of oil. Consequently most newly installed boilers are now of the condensing variety (Utley and Shorrock 2008).

The UK government's 'Heat Call for Evidence' (BERR 2008g) gives estimates of delivered energy demand for space heating of the housing stock separated into three age categories: pre-1996; new-build; and future buildings. Houses built before 1996 have

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<sup>6</sup> 'Full insulation' is defined as "at least 100mm of loft insulation where a loft is present; cavity wall insulation where there is a cavity; and at least 80% of windows being double-glazed" (Utley and Shorrock 2008).

<sup>7</sup> SEDBUK – Seasonal Efficiency of Boilers in the UK

substantial average delivered energy demands of approximately 49 GJ/yr; similar to the average UK household of Figure 4-1. In contrast, houses built under current building regulations have average loads of just 7 GJ/yr, while those built under the 'Building a Greener Future' initiative (moving towards zero carbon homes) are intended to have demands close to zero (BERR 2008g). However, it is estimated that the majority of the housing stock standing in 2050 already exist; two-thirds of the 2050 stock according to the Communities and Local Government Committee (2008), and four-fifths according to Boardman (2007). Retrofit improvements therefore have a vital role to play for sector-wide efficiency improvements. The UK Government's recent 'Heat Call for Evidence' indicated that 'feasible' improvements could reduce the average delivered-energy demands of existing buildings by around 40% to 32 GJ/yr (9 MWh/yr; BERR 2008g), apparently on the basis of Oxford University's '40% House' research (Boardman et al. 2005).

#### 4.3.4 Variation of the mean

There is a large variance of household energy use for heating (Hawkes and Leach 2008). Ideally, a representative distribution would be presented to indicate this variation; but constraints with sample data prevented this at the time of writing. However, the Carbon Trust published an interim report covering their micro-CHP and condensing boiler trial in 2007 (Carbon Trust 2007), and had just released the underlying dataset as this thesis was being written. These data include a year's worth of 5-minute heat demand data (space and water heat) for 98 residential buildings, and future work could therefore look into more detail at how these heat demands vary around mean values.

#### 4.3.5 Space-heating summary

In summary, there is a clear trend towards increasing comfort levels, which are expected to saturate at around 19–20°C as an average internal temperature. These temperature levels (the energy service) drive the demand placed on a space heating system, which is also influenced by the external temperature (and hence season) and the size and thermal characteristics (insulation levels) of the building. The efficiency of the heating system then determines the quantity of fuel or electricity required from the energy supply system.

Opposing the trend of increasing temperature levels has been the increasing levels of both insulation and heating-system efficiency. Though the effect of these improvements is difficult to estimate, Utley and Shorrock (2008) suggest that without them delivered-energy use for space heating would have doubled since 1970. The net result of increasing temperature levels and improving efficiency levels has been in a broadly constant delivered-energy use for space heating since 1970 in the average household; an annual value of generally between 45 and 50 GJ/yr.

There is a large scope for further efficiency improvements. More than four-fifths of the housing stock lack 'full insulation' (Utley and Shorrock 2008), and while the sector-wide average heating-system efficiency was estimated as 74% in 2006 (*ibid*), recent best practice boiler efficiencies (GCV) are 90% (Energy Saving Trust 2005b). Since it is likely that temperature levels will saturate in the average household, average delivered energy

demand could fall in the future as further insulation and heating-system efficiency improvements are made.

There are many factors influencing the improvement process, including building regulations, cost, consumer-awareness, hassle-factor, and so on. In the cases of new builds, certain existing-building alterations, and boiler replacements, building regulations stipulate good thermal properties and high boiler efficiencies (Office of the Deputy Prime Minister 2006a and 2006b). It is estimated, however, that the majority of the housing stock standing in 2050 already exist; two-thirds of the 2050 stock according to the Communities and Local Government Committee (2008), and four-fifths according to Boardman (2007). Retrofit improvements therefore have a vital role to play for sector-wide efficiency improvements. Some forms of insulation, such as loft insulation, are inherently financially attractive and appear to have saturated the building stock where possible. While there is a great potential for further insulation, it is currently less financially attractive for the average householder. The Committee on Climate Change (2008) recently indicated, however, that insulation is one of the most cost-effective methods reducing carbon emissions in the residential sector, and hence it may be that interventions of some form improve the financial case for insulating existing buildings.



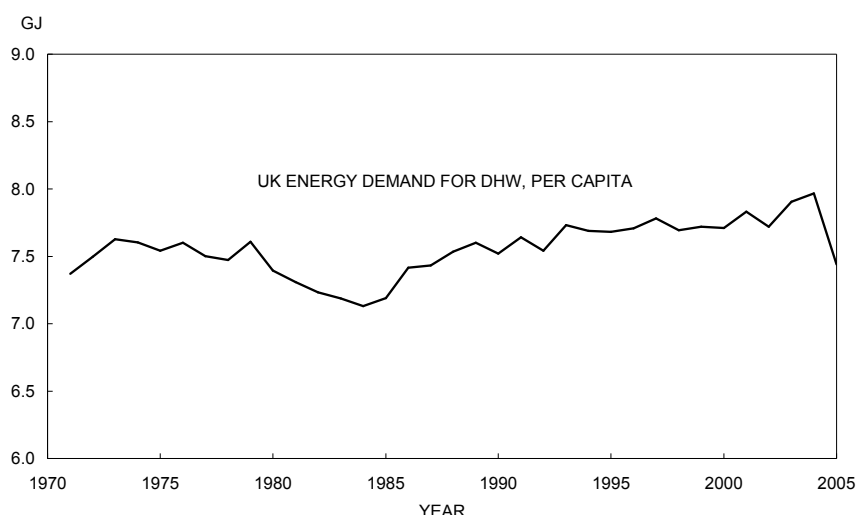
## 4.4 WATER HEATING

### 4.4.1 Factors affecting delivered energy demand

Behavioural factors influencing the quantity of delivered fuel or electricity used for water heating include the desired delivery temperature and volume of hot water; the use of storage tank thermostats; the use of timers to schedule water heating; and the number of occupants in the household. Technological factors include the type of heating system employed and the level of hot water tank insulation (if a hot water tank is present).

### 4.4.2 Trend and variation of annual energy service demand for DHW

There does not appear to be a direct data source with which to indicate the trend in end-user hot water demands. However, while efficiency improvements have been made in terms of increased levels of water tank insulation (where hot water tanks are used) and increased levels of boiler efficiency (Utley and Shorrocks 2008), the average per capita delivered-energy demand for hot water is estimated to have been broadly constant, as indicated by Figure 4-3. This implies that the quantity of hot water used by the average person has increased over recent decades.



**Figure 4-3: Annual UK per capita delivered-energy demand for hot water**  
(Based on DTI 2007a)

The energy service desired by the householder is a certain volume of water at a specified temperature. While the volume of hot water used by the households varies widely even between otherwise similar households, (BSI 1989), a recent hot-water-use monitoring project confirmed that it is primarily dependent on the number of occupants (Energy Saving Trust 2008). This monitoring project analysed the hot water consumption characteristics of approximately 120 households, including the volumes and temperatures of hot water used by households, the time at which this water was used, and the end-uses it served (Energy Saving Trust 2008).

Table 4-1 summarises a variety of available sources, including the recent Energy Saving Trust (EST) report, all of which estimate both the volume and temperature of hot

water used in households. The EST values are the most recent and transparent of the sources, and hence they were considered the most reliable for the determination of household hot water demands (summarised below). The other sources, however, give a useful indication of a possible range around the EST values. Some of the sources in Table 4-1 suggest that demand is exactly proportional to the number of occupants, but others, and notably the EST values, suggest that there is a base amount of hot water that any household uses, above which the effect of occupancy then accrues.

**Table 4-1: Daily household hot water usage**

Source	Description	Volume (litres)	Temp (°C)
BSI 1989	Low	30N	55
	High	40N <sup>†</sup>	55
BSI 2006a	Low	35N	60
	High	45N	60
The German Solar Energy Society 2005	Low	(20 to 30)N	45
	Average	(30 to 50)N	45
	High	(50 to 70)N	45
Yao and Steemers 2005		65N	40*
BRE 2002	Very low	-40%	60
	Low	-20%	60
	Average	33 + 25N	60
	High	+20%	60
Energy Saving Trust 2008	Whole sample	46 + 26N	53
	(N ≤ 5)	40 + 28N	53

N = Number of occupants in a household

<sup>†</sup> Higher volumes (35 L to 40 L) are 'common for lower occupancies – one or two person households' (check quote)

\* Weighted average of a range of different end uses at varying temperatures

The average occupancy of UK households has been slowly decreasing over recent decades, but was broadly constant at approximately 2.4 between 1995 and 2006 (Appendix A). Combining this with either EST model (either 'whole sample' or 'N ≤ 5') gives a representative run-off volume of approximately 110 litres/day. Given this required volume of water, the heat required,  $Q_{demand}$ , to raise the temperature of the water to a specified delivery temperature may be calculated as follows:

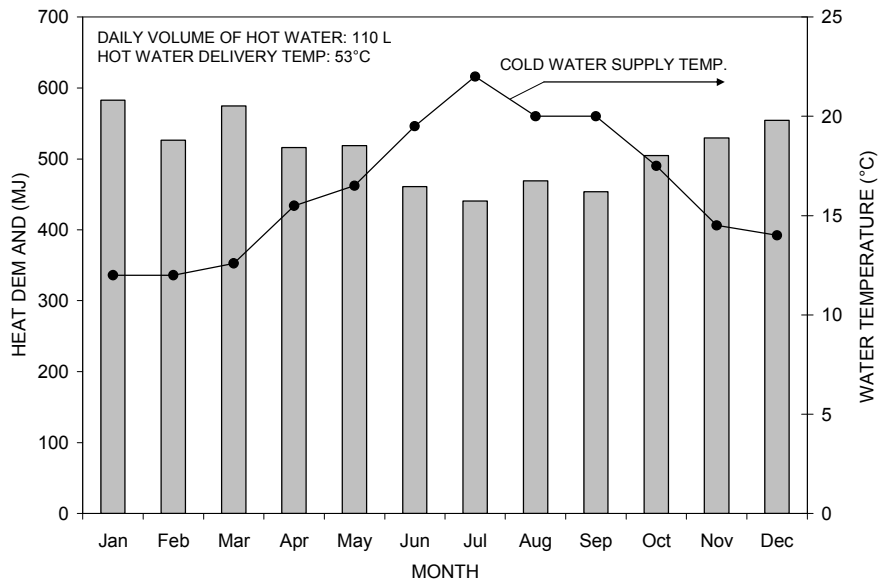
$$Q_{demand} = mc_p (T_{delivery} - T_{inlet}) \quad 4-1$$

where  $m$  is the mass of the water,  $c_p$  is its specific heat capacity<sup>8</sup>,  $T_{delivery}$  is the required delivery temperature and  $T_{inlet}$  is the cold water supply temperature.

The daily runoff volume of 110 litres was converted to a monthly hot water mass (1 litre = 1 kg), and used in Equation 4-1 with monthly average inlet and delivery temperatures reported by the EST study (Energy Saving Trust 2008), to produce Figure 4-4. The EST study reported that for regular boiler installations (a boiler with a hot water storage tank – appropriate for the solar hot-water system assessed in Chapter 6), the mean

<sup>8</sup> The appropriate British Standard (BSI 2006b) states that the value used for the specific heat capacity should correspond to the mean fluid temperature.

delivery temperature of the sample was 53°C. Monthly average inlet (supply) temperatures varied significantly with season, and for regular boiler systems ranged between approximately 12°C and 22°C as shown on Figure 4-4, with an annual average of 16°C.



**Figure 4-4: Monthly hot water demand and cold water supply temperature**

Figure 4-4 indicates that increased inlet temperatures during the summer months reduce the water heating demand. The lowest demand occurs in July, and is approximately three-quarters of the largest demand that occurs in January. The sum of all months gives an annual demand of 6130 MJ<sub>th</sub> (1700 kWh<sub>th</sub>) for an average, 2.4 person household, which is the heat required to raise 40150 litres of water to 53°C. These numbers are based on the EST model of household hot water demand given in Table 4-1. The other models given in Table 4-1 were used to give comparative heat demand estimates, and for 2.4 people they equate to a range of 2130–7500 MJ<sub>th</sub>/yr, which is 35–122% of the EST-based estimate. While this is a significant variation, it is considered here that the EST values are the most reliable, since they are based upon a transparent monitoring project. They are therefore taken forward for further discussion.

The delivered energy required to provide a given quantity of hot water depends upon both the system losses between the taps and the heating system, and the conversion efficiency of the heating system. Both are estimated and specified in Chapter 6 during the process of estimating the delivered fuel or electricity displaced by the use of a SHW system. The overall conversion efficiencies between either fuel (in NCV terms) or electricity and the hot water provided to the end-user are estimated as 63%, 60%, and 75% for a new gas boiler, new oil boiler, and electrical immersion heater respectively. Dividing the annual hot water demand by these values gives annual delivered energy demands of 9.7 GJ<sub>NCV</sub>, 10.2 GJ<sub>NCV</sub>, and 8.2 GJ<sub>e</sub> for the gas boiler, oil boiler, and electricity immersion heater, respectively. Converting the fuel values to GCV terms, for consistency with UK energy

statistics, gives 10.8 GJ<sub>GCV</sub>/yr for the gas boiler scenario and 10.9 GJ<sub>GCV</sub>/yr for the oil boiler scenario.

This selection of delivered energy values are notably lower than those given in Figure 4-1 (p.60), where 18.3 GJ/yr is the BREHOMES-estimated value for delivered-energy use for water heating in 2006. There are a number of likely reasons for this. Section 4.2 outlined that the majority of the UK housing stock uses boilers for hot water provision (which are less efficient, within the household, than electrical immersion heaters), and the average conversion efficiency of heating systems across the UK was given as 74%. The boilers considered above, however, were assumed to comply with 2005 building regulations and be 85–86% efficient, and therefore their fuel-requirements are lower than the average heating system across the UK. Another likely reason is the differing approach to hot water demand modelling taken by the BRE. This is shown in Table 4-1. Though the BRE assume a slightly lower value for daily runoff volume than the EST-derived estimates above, they assume a significantly higher hot water delivery temperature and hence temperature rise required from the heating system. The EST study indicated that the BRE model will overestimate hot water demands by 35% due to the excessive temperature rise assumed (Energy Saving Trust 2008), which in turn will overestimate the delivered energy demand presented in Figure 4-1. (Some delivered-energy use may therefore have been erroneously allocated in Figure 4-1: it is probable that space heating should be higher and water heating lower.)

#### 4.4.3 Trend of mean household delivered energy demand

In the average household, delivered energy use for water heating is estimated to have decreased by 18% over the period 1970–2006 (Figure 4-1). The UK Government's 'Heat Call for Evidence' (BERR 2008g) estimates that delivered energy usage for water heating will now remain constant in the near-future. It is currently ~18 GJ/yr, and they expect similar loads even for new homes moving towards the 2016 'zero-carbon' target (annual, net carbon emissions from all energy use equalling zero; DCLG 2007, BERR 2008g). Although the underlying reasons are not given, this implies that demand for hot water will increase as the efficiency of heating systems improves, each cancelling the effect of the other and resulting in a constant delivered energy demand. In contrast to this implied expectation, there is evidence that modern water saving equipment can reduce that volume of water used and hence the energy requirement for hot water in households (Thur et al. 2006). Further research is recommended in this area.

#### 4.4.4 Water-heating summary

In summary, the quantity of hot water used within a household – the energy service desired by the householder – depends primarily upon the number of occupants. For regular boiler installations an average annual temperature rise of 16 to 53°C is required from the boiler, and in the average, 2.4-person household the daily runoff volume is currently 110 litres. This equates to an annual hot water demand of 6.1 GJ<sub>th</sub>/yr, which is spread fairly evenly across the year although summer months have lower demands than winter months. Assuming modern gas, oil or electrical heating systems, it was estimated

8–11 GJ/yr of delivered energy would be required to satisfy this demand (the lower end being electricity, the higher end being gas or oil). This is notably lower than the average UK household energy use of 18 GJ/yr (Figure 4-1; p.60). There are two likely factors contributing to this disparity. First and foremost, the average heating-system within the housing stock is lower than those of the assumed modern systems, and secondly the BRE's estimation methodology underlying the figure of 18 GJ/yr may be assuming an excessive temperature rise (and hence overestimating the delivered energy use for water heating, which should probably instead be allocated to space heating).

There appears to have been a trend of increasing hot water usage per person. This was implied because delivered energy demand for hot water has been approximately constant since 1970, while heating system efficiencies and storage tank insulation levels have increased. The UK Government's 'Heat Call for Evidence' (BERR 2008g) estimates that delivered energy demands for water heating will remain constant into the near future, which again implies that though heating systems will become more efficient (enforced by building regulations), the hot water demands of end-users will also increase.

## 4.5 END USES OF ELECTRICITY

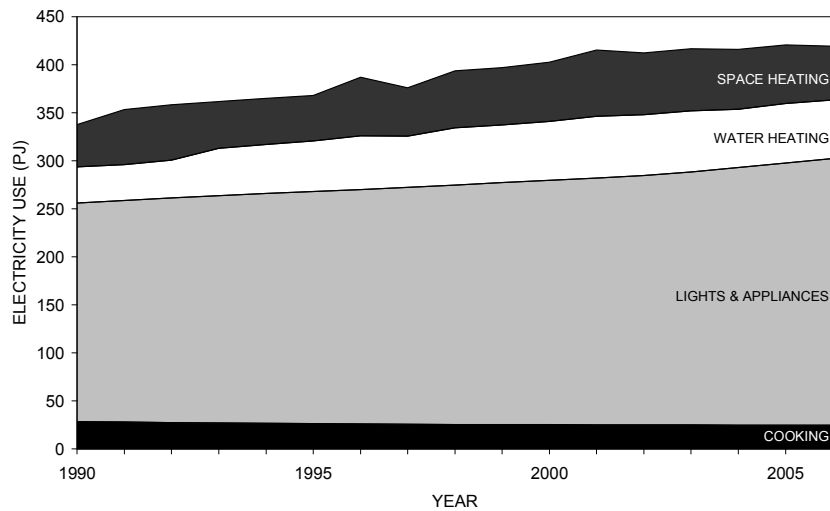
### 4.5.1 Factors affecting delivered energy demand (electricity use)

Electricity is a very different energy carrier to the fuels that provide the majority of the residential sector's space and water heating. Like fuels it can be, and is, used to supply low-quality space and water heating, but it can also conveniently provide refrigeration, illumination, communication, entertainment, and many more energy services. Since the end-uses of electricity vary widely, it is unsurprising the factors affecting electricity use vary significantly; both technological and behavioural. Behavioural factors include the number of appliances owned and the frequency with which they are used, and there is also a non-linear relationship between household size and electricity use (larger households generally using more, but proportionately less per occupant than smaller households; Jardine 2008). Contributing to this relationship are some floor-area related factors, such as lighting requirements (BRE 2002).

### 4.5.2 Trend of energy service demand

It is by no means trivial to list and quantify the energy services provided by electricity within households, since their number is now substantial. Owen (2006), for example, suggests that the number of appliances found in a typical home rose from about 17 in the 1970s to almost 50 in the 2000s. Since the quantification of electricity-based energy services is not central to this thesis, it is left as further work. Instead, the discussion remains at the stage of delivered energy (Appendix B), and total electricity use is broken down into various categories. This enables certain useful trends in use to be identified, and also gives an indication of the different magnitudes of differing end-use categories. Sector-wide values are used rather than average households at this stage, since some categories, such as space heating, only apply to a small proportion of households (2.5 million of the total 26 million in 2006; Utley and Shorrock 2008), and therefore an 'average house' does not use electricity for space heating.

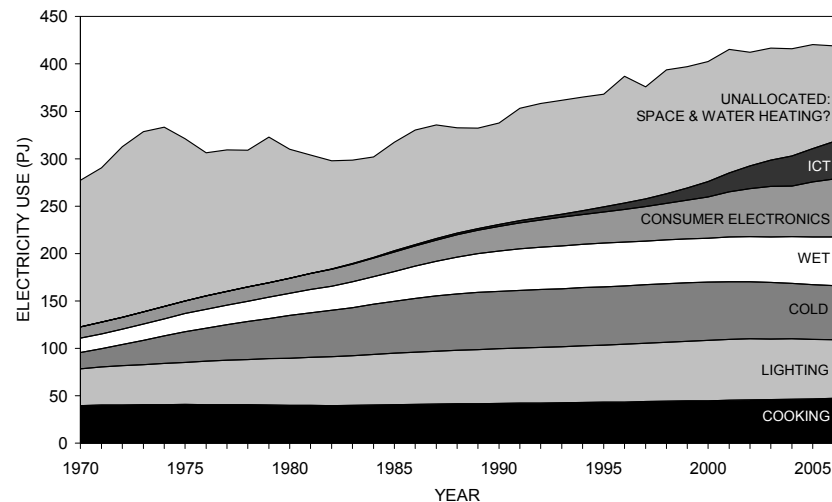
At a national level, there are two principal sources that provide estimates for disaggregated residential electricity consumption by appliance categories, both reported in the Government's 'Energy Consumption in the UK' publication (BERR 2008e). The first is the modelling carried out by the Building Research Establishment (BRE), which covers the period since 1990. The categorisation is broad, covering 'space heating'; 'water heating'; 'cooking'; and 'lights and appliances', and the estimated 1990–2006 breakdown is given in Figure 4-5. This indicates that 'lights and appliances' are by far the largest user of electricity and that they have driven the overall increase in the residential sector's electricity use.



**Figure 4-5: BRE-based estimates for disaggregation of residential electricity consumption by end use, 1990–2006**

(Source: BERR 2008e Table 3.7)

The second source of disaggregated electricity use is DEFRA's 'Market Transformation Programme' (MTP), whose estimates extend back to 1970. These estimates are similar to those of the BRE in that they are made on the basis of 'bottom-up' modelling. In this case they used estimates of the annual energy usage of appliances and the penetration of those appliances throughout the residential sector. The disaggregation provided by the MTP is presented in Figure 4-6, where the unallocated remainder of electricity use is also presented. The MTP data has the advantage of greater disaggregation than the BRE-based estimates of Figure 4-5, though it excludes electrical space and water heating. The MTP categorisation is: 'cooking' (hobs, ovens, microwaves and kettles); 'lighting' (internal); 'cold' (chest freezers, upright freezers, fridge-freezers and refrigerators); 'wet' (dishwashers, washing machines, tumble driers and washer-driers); 'consumer electronics' (TVs, video players and recorders, set-top boxes and external power supplies/battery chargers); and 'ICT' (computers, monitors, printers).



**Figure 4-6: MTP estimates for disaggregation of residential electricity consumption by end use, 1970–2006**

(Adapted from BERR 2008e; Tables 3.1 and 3.10)

During the comparable period 1990–2006, the two estimates shown in Figure 4-5 and Figure 4-6 for lighting, appliance-use and cooking are broadly similar, although there are some differences in the detail. The MTP figure is within 10% of the BRE figure throughout the period (no more than 25 PJ below or 16 PJ above). Underlying this, however, the MTP estimate for electrical cooking has been consistently larger than that of the BRE, 50% larger in 1990 going up to 100% larger (47 PJ compared to 25 PJ) in 2006.

Figure 4-6 indicates that electricity use by lighting, appliance-use, and cooking has accounted for approximately 70–75% of total residential sector electricity use between 1990 and 2006, during which time the remaining unallocated portion has varied between roughly 100 and 130 PJ/yr. This is approximately equal to the BRE-based estimate for space and water heating (Figure 4-5), which indicated that 50–60 PJ/yr has been used for space heating and similar for water heating for the majority of 1990–2006. It therefore appears reasonable to assume that most of the unallocated proportion on Figure 4-6 would be accounted for by space and water heating, at least back as far as 1990 if not further.

Looking back as far as 1970, the MTP estimates that electricity use for lighting, appliance-use and cooking has grown an extraordinary 159% since 1970 (Figure 4-6), compared to the number of households and people which grew 29% and 10% respectively (Appendix A). This indicates that the average household electricity use for these end-uses has grown by 86% since 1970, while average per capita use has grown 138%. The increase was driven initially by cold appliances, and more recently by wet appliances and then the fast-moving categories of consumer electronics and ICT (growing 41% and 145% since 2000 respectively). Lighting has also steadily grown. Table 4-2 indicates that the Market Transformation Programme's recent 'reference' (Business as Usual - BAU) scenario estimates that out to 2020 the consumer electronics and ICT categories will show by far the



most significant growth, and that at that time they will together account for 44% of the electricity used by residential appliances (compared to 34% in 2007).

**Table 4-2: MTP scenarios for electricity use by residential appliances in 2020**

	2007: Base year	2020: Reference (BAU) scenario		2020: 'Feasible product policies' (P1) scenario		P1 savings
	PJ	PJ	% growth	PJ	% growth	PJ
ICT	43	53	22%	39	-30%	10
Consumer electronics	67	122	84%	53	2%	3
Wet	52	56	8%	32	-48%	37
Cold	56	49	-12%	82	23%	41
Lighting	62	69	11%	26	-40%	27
Cooking (electric)	47	47	-1%	44	-7%	3
<b>TOTAL</b>	<b>327</b>	<b>396</b>	<b>21%</b>	<b>276</b>	<b>-15%</b>	<b>120</b>

(Adapted from: Market Transformation Programme 2008)

### 4.5.3 Trend of mean household electricity use

During this and the following section, average household values are presented to enable later comparison with estimated electricity micro-generator outputs. Both are presented in terms of kWh since this is an intuitive unit for electricity. From this point onwards, therefore, there will be a transition to the use of kWh when describing electricity use. (If conversion to GJ is required, multiply kWh by 0.0036.)

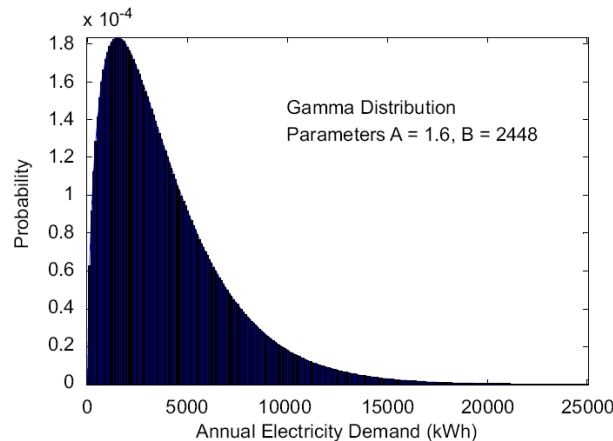
As Figure 4-6 previously indicated, annual delivered electricity use in the residential sector rose by 51% from 277 to 419 PJ/yr (77 to 116 TWh) between 1970 and 2006, while the number of households grew by 40% (Appendix A). The mean household electricity use has therefore been broadly constant; it was 14.9 GJ/yr (4100 kWh/yr) in 1970 and has levelled at approximately 16.3 GJ/yr (4500 kWh/yr) between 1996 and 2006. Over the period 1970–2006 the average generation efficiency of the grid increased from 27% to 35% (Figure 3-7) and so the increase of overall annual primary energy used for residential electricity provision was relatively constrained to 16%.

Table 4-2 showed MTP estimates of future demand for a 'reference' (Business as Usual) scenario, in which sector wide electricity use for residential appliances (this excludes space and water heating) will grow to approximately 400 PJ/yr by 2020. In contrast, under a 'P1' (feasible product policies) scenario it could fall to 280 PJ/yr (Market Transformation Programme 2008). Given the MTP's household number estimates (*ibid*), the reference scenario represents 14 GJ/yr (3900 kWh/yr) per household, while the P1 scenario represents 10 GJ/yr (2700 kWh/yr) per household. Since these figures do not include electricity use for space and water heating, it is more appropriate (though still imperfect) to compare them with the 'standard' tariff values outlined below, which are 14.4 GJ/yr (4000 kWh/yr) for 2006. This suggests that electricity use in the average household could either remain approximately constant or fall from the current levels in the future, though further work is recommended to examine this in more detail.

#### 4.5.4 Variation of and around the mean

The mean annual electricity use of households varies with geographical region. In 2006 the lowest regional mean was 3800 kWh/yr in the north-east of England while the highest was 4900 kWh/yr in the east of England (BERR 2008a). This is a significant difference of approximately 1100 kWh/yr. Another notable influence on mean electricity use, for which statistics are available, is that of differential (time-of-day-dependent) electricity tariffs. 'Economy Seven' tariffs were developed to encourage the use of electrical night storage heaters, in order to increase the night-time residential load and create a more balanced and hence favourable use of the electricity network across 24 hours (Section 3.4.2). The mean usage for British households with Economy Seven tariffs was over 50% larger than those with standard tariffs; 6200 kWh/yr compared to 4000 kWh/yr in 2006 (BERR 2008d). It appears, therefore, that night-storage heaters use something like 2000 kWh/yr, since these are a predominant reason for using Economy Seven tariffs. As a further indicator of the difference between Economy Seven and standard tariffs, the UK Government, when producing their 'Quarterly Energy Prices' publication (DECC 2008), uses 6600 kWh/yr as representative of households with Economy Seven tariffs (of which 3600 kWh/yr is assumed to be used during off-peak times), compared with 3300 kWh/yr for households with standard tariffs. Clearly the presence of Economy Seven tariffs, and the associated electricity-using behaviour involving largely storage heating, has a significant influence on a household's annual electricity use.

It is useful, where possible, to present a distribution of the annual electricity use of households around the (arithmetic) mean value. Figure 4-7 shows an estimate of the distribution of annual electricity demand for England, calculated by Hawkes and Leach (2008). This gamma distribution is based on monitored electricity use from the occupied households of a sample of 60 dwellings in Milton Keynes Energy Park during 1988–91 (which were predominantly gas-heated; T. Oreszczyn, University College London, 26/03/2009, personal communication). There is a clear positive skew, and as a result the mean value of 3900 kWh/yr is skewed upwards from the majority of the sample by a relative minority of households that are using a large amount of electricity. This is close to the 2006 mean household usage for standard tariffs (above). In contrast to the mean, the median is the value at which half the households are below and half above, while the mode is the most likely value and hence favours the larger number of households with lower electricity usage. Hawkes and Leach (2008) give the median as 3300 kWh/yr, which incidentally is the same as the values used by the UK Government (above) to represent standard tariffs. The mode may be calculated from the gamma distribution parameters (Montgomery et al. 2007), and in this case equals approximately 1500 kWh/yr.



**Figure 4-7: Estimated probability density function for annual electricity demand in England, 1988–91**

(Reproduced with permission from Hawkes and Leach 2008)

The gamma distribution of Figure 4-7 is not necessarily a good representation of English (or even UK) households in general. An 'Energy Park' may not involve a representative spread of households in the first place, and furthermore the sample size of 60 households is very small compared to the total of 26 million UK households in 2006 (Appendix A). It is therefore worth corroborating the numbers quoted above as far as possible. The BRE's 'Energy Use in Homes - Fuel consumption' report (BRE 2005a) includes a histogram of electricity use that is based upon a much larger data sample of more than 7000 English households<sup>9</sup>. The BRE histogram, like that presented by Hawkes and Leach, shows considerable variation and positive skew but has different average values. The mean of the BRE sample is 5300 kWh/yr; considerably higher than the value of 3900 kWh/yr given by Hawkes and Leach (2008). In this case, households with electrical space heating are included in the sample and hence it is perhaps more appropriate to compare the BRE mean value with the overall UK mean of 4500 kWh/yr (although the relative proportion of BRE-sample households with electrical heating is unknown). The BRE's modal range of '3000–4000 kWh/yr' (the histogram was split into bins of 1000 kWh/yr) is also higher than the mode of 1500 kWh/yr implied by Hawkes and Leach's gamma distribution. Unfortunately the BRE did not give a median value to enable a median comparison. The BRE report (BRE 2005a) is the more comprehensive as it is based on thousands of properties rather than tens of properties, and the modal range of 3000–4000 kWh/yr was therefore considered to be appropriate for further use within this research.

<sup>9</sup> The BRE report (BRE 2005a) is based upon a combination of the 2001 English Housing Condition Survey (EHCS) – a sample of tens of thousands of homes (DCLG 2001) – and follow-up readings of 7370 EHCS addresses covering the period 2000–2001.

#### 4.5.5 Electricity-use summary

Electricity is a flexible energy carrier and it is used, to varying extents, to provide all energy services in the residential sector. Unsurprisingly this variation of applications gives rise to a wide range of factors affecting residential electricity use. Behavioural factors include the number of appliances owned and the frequency with which they are used, and there is also a (non-linear) relationship between household size and electricity use. The wide variety of end uses (around 50 since the early 2000s) has prevented the quantification of the energy services in this section, but though it is preferable to do so it is not essential for this thesis since the focus is on micro-generator performance. Instead, end-uses were categorised and then quantified in terms of the delivered electricity used in each case.

Electricity is used for space heating in a relative minority of households (approximately 2.5 million compared to the total 26 million in 2006) but is estimated to have amounted to between 50 and 60 PJ/yr (14–17 TWh) for the majority of the period 1990–2006; roughly 15% of the total residential sector electricity use. During the majority of same period water heating in households also accounted for approximately 50–60 PJ/yr (the number of households with water heating was unknown at the time of writing). Together, these two end-uses have accounted for approximately 30% of the residential sector's total annual electricity use since 1990. The remaining 70% have been made up of a range of end-use categories: cooking; lighting; cold; wet; consumer electronics; and ICT. Looking back as far as 1970, electricity use for these end-uses is estimated to have grown an extraordinary 159% (or 86% per household or 138% per capita). Consumer electronics and ICT are now the fastest growing categories, and the MTP estimates that consumer electronics in particular will continue this trend out to 2020 under a 'business as usual' scenario (Table 3-1).

The mean UK household used 4100 kWh/yr in 1970. This fluctuated but grew slightly until 1996 where it has since levelled at approximately 4500 kWh/yr. Mean annual usage varies regionally across the UK, and in 2006 the highest users residing in the east of England (mean = 4900 kWh/yr) and the lowest in the north-east of England (mean = 3800 kWh/yr). The type of tariff a household uses has a significant affect on their annual usage. In 2006 the mean household with a standard tariff used 4000 kWh/yr compared to the mean 'Economy Seven' household at 6200 kWh/yr. It is likely most of this extra usage is accounted for by night-storage heaters.

It appears that a majority of households will in fact reside below mean annual values, since the data sample distributions from both Hawkes and Leach 2008 and the BRE 2005a are positively skewed. Median and modal averages are alternative and complementary values that can be used to further describe electricity use, however unfortunately neither of the data samples summarised above are ideal representations of the wider population of UK households. The BRE's sample (BRE 2005a) is the more comprehensive as it is based on thousands of properties rather than tens of properties, and the modal range of 3000–4000 kWh/yr was therefore considered to be appropriate for further use within this research (the BRE report did not publish a median value). This modal range is used in later chapters,

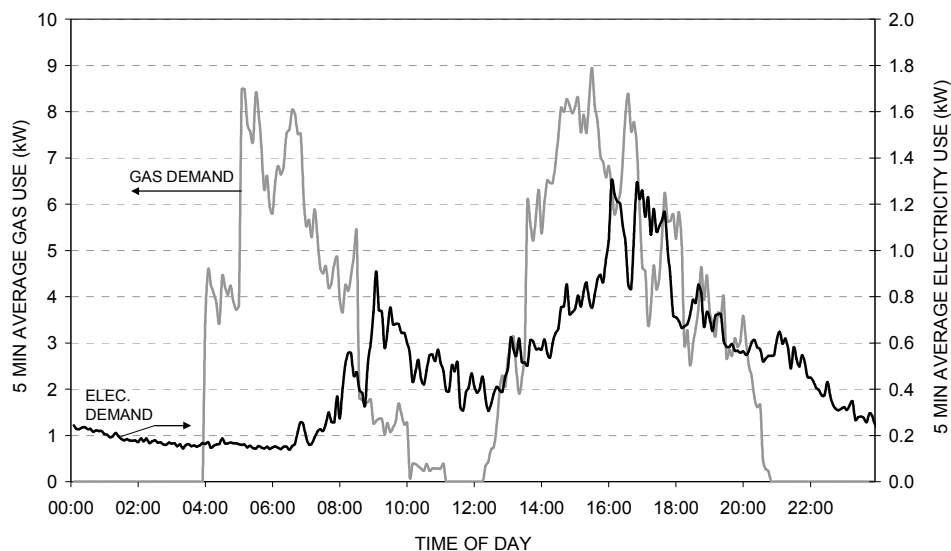
along with mean values, to give context to the electricity outputs of the assessed electricity micro-generators.

To give an idea of future possibilities, the MTP's 'business as usual' scenario suggests that the mean household in 2020 will use 3900 kWh/yr, not including any allowance for space or water heating (Market Transformation Programme 2008; Market Transformation Programme 2007). Under the MTP's 'P1' (feasible product policies) scenario this would reduce to 2700 kWh/yr. It is most appropriate to compare these values with the 'standard' tariff mean of 4000 kWh/yr, which suggests that total electricity use per household will not change significantly in the near future, and could in fact decrease although this requires a change in current trends.

#### 4.6 DAILY ENERGY USE PROFILES

The demand for useful energy within households is determined almost exclusively by the end-users, and is generally uncontrollable from the point of view of the supply system. There are exceptions to this, such as the introduction of Economy Seven tariffs to guarantee electrical loads at predictable times during the night (which are also, in some cases, adjusted by the network via radio teleswitch technology; Boait et al. 2007).

Figure 4-8 shows that energy demands can vary significantly during the course of the day. This figure gives the average daily gas and electricity use of a household participating in the Carbon Trust's recent micro-CHP field trial (Carbon Trust 2007), during a winter month. There are significant average gas (and hence heating) demands (above 8 kW as a 5 min average) in the early-morning and early-evening, whereas the gas demand is zero during the night and at midday. In contrast, the electricity demand peaks slightly after the peak gas demand in both morning and evening, suggesting the use of a heating timer to warm the house up prior to its occupants becoming active within it. It is also clear from Figure 4-8 that the household has an electrical load throughout the day and night, implying the existence of 'base-load' appliances such as refrigerators and freezers. The electricity demand is significantly smaller than the gas demand (note the differing axes); the peak demand is around 7 times smaller. This is likely to be representative of many UK households, since annual delivered energy demands for space and water heating constitute the vast majority of the total in the average UK household (Figure 4-1).



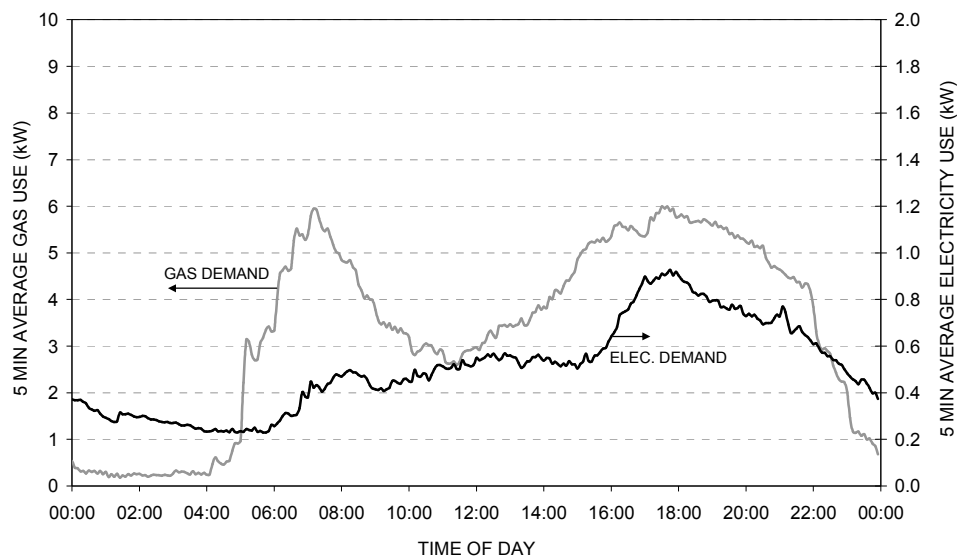
**Figure 4-8: 5-min average gas and electricity demand for a single household, for an average day in a winter month**

(Source: Carbon Trust 2007)

The five-minute averaging associated with the demands shown in Figure 4-8 are a compromise; they reduce the data-logging requirements and computational expense associated with higher-resolution (shorter time-period) measurements, but will flatten any peaks and troughs whose duration is less than five minutes. Kettles, for example, are

relatively high-power, short-duration appliances, using something like 2–3 kW for a couple of minutes. When represented by a five-minute average, they will appear as a lower-power, longer-duration load. Nevertheless, the five-minute data provided by the Carbon Trust (Carbon Trust 2007) is a major step forward from the prominent half-hourly or hourly datasets.

A similar averaging problem exists when representing groups of households; the five-minute peaks and troughs of any one household are likely to be flattened due to variation in the demands across all households at any one time. This disadvantage drove the use of Figure 4-8 (above), but on the other hand averages taken over a number of households will usefully indicate representative trends if they exist. Thus the presentation below of Figure 4-9, which shows the average demands of around 100 households during an average day within a winter month.



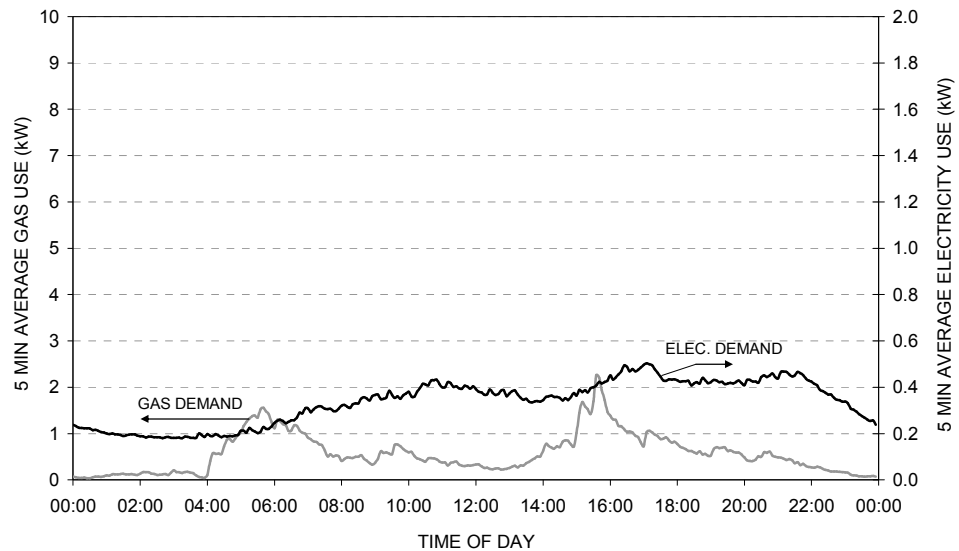
**Figure 4-9: 5-min average gas and electricity demand, as an average of ~100 households across a winter month**  
(Source: Carbon Trust 2007)

Figure 4-9 suggests that the broad shape of the curves in Figure 4-8 are representative of households in general – there are both morning and evening peaks and the electrical demand peaks slightly after the gas (heating) demand peaks. As might be expected, the averaging across many households has flattened the curves; gas demands peak at 6 kW rather than almost 9 kW, while electrical demands peak at 0.9 kW rather than 1.3 kW.

Underlying the daily trends may be very different occupancy patterns (e.g. full-time workers who are out during the day, part-time workers who are in some of the day, or those who remain at home more of the time). These are unidentifiable from the figure since it is an amalgamation of many households, but will no doubt have an impact on individual household demands. Such issues are being addressed with the research consortium that the work of the present author contributes towards (see, for example, Richardson et al. 2008

or Jardine 2008) but they are beyond the scope of this discussion, which aims simply to identify typical daily energy use patterns.

Figure 4-9 can be contrasted with Figure 4-10, which shows demand profiles during an average day over a summer month. This indicates that both heat and electricity demands are lower during summer months.



**Figure 4-10: 5-min average gas and electricity demand, as an average of ~100 households across a summer month**  
(Source: Carbon Trust 2007)



#### 4.7 INSIGHTS FROM EXERGY ANALYSIS

Up to this point, all energy uses within households have been discussed in terms of the First Law of Thermodynamics; the principle of energy conservation. It was shown in Chapter 2 that in many cases this can be an insufficient representation of an energy interaction, since it ignores the quality of energy interactions. The concept of *exergy*, which incorporates the Second Law, can provide such information. This section provides some insights drawn from exergy analysis regarding the use of energy within households.

Residential fuel-fired and electrical (space) heating equipment is used to supply heat at a constant temperature (assuming source and sink are thermal reservoirs; see Section 2.4.3). Rosen and Dincer (1997) give the energy efficiency of electrical heating at constant process temperature as:

$$\eta = \frac{Q_p}{W} \quad 4-2$$

where  $Q_p$  is the heat transfer and  $W$  is the work input (electrical input). Similarly, the exergy efficiency is the ratio of the exergy output to the exergy input, where the exergy output may be calculated using Equation 2-3 (p.27):

$$\psi = \frac{E^{Q_p}}{E^W} = \frac{\left(1 - \frac{T_0}{T_p}\right) Q_p}{W} = \left(1 - \frac{T_0}{T_p}\right) \eta \quad 4-3$$

Rosen and Dincer go on to show that a similar expression is approximately correct for fuel-based heating systems. Thus, in the case of heat transfer at a constant temperature the exergy efficiency is directly proportional to the energy efficiency – it depends only on the ratio of the process to reference temperatures (Hammond 2004a).

Energy and exergy conversion efficiencies within a representative UK household are summarised in Table 4-3 for space heating, as well as for the three other end-use categories given earlier in Figure 4-1. Space heating energy efficiencies were taken from Utley and Shorrock (2008), who provide estimates of sector-wide average efficiencies between 1970 and 2006 (Section 4.3.3). Space heaters are assumed to be fossil-fuel fired, since they have been in the main type of heater for the entire period. Utley and Shorrock's efficiencies were used to estimate the associated exergy efficiencies via Equation 4-3, assuming a process temperature of 55°C and reference (environment) temperature of -1°C, the typical winter exterior design temperature (reference sources given in Table 4-3). Summary figures for 1970 and 2006 are presented in Table 4-3, which also shows estimated energy and exergy performances for other end-use technologies. An electrical cooker was chosen to represent the cooking category. This was an arbitrary choice for illustrative purposes (around half of all residential cooking is electric; Figure 4-2). Since cooking is such a small energy-using category, the choice between fuel and electrical cooking makes relatively little difference.

**Table 4-3: Energy and exergy efficiencies for end-use appliances (delivered to useful energy) in an average household**

End-use technology	Process temperature, $T_p$	Energy efficiency, $\eta$	Exergy efficiency <sup>‡</sup> , $\psi$
Fuel-based space heater (fuel input to hot water output)	55°C* 328 K*	Varying over time, housing-stock average of 49% in 1970; 74% in 2007 based on GCV of fuel <sup>+</sup>	Varying over time, housing-stock average of 8% in 1970; 13% in 2007 based on GCV of fuel <sup>+</sup>
Fuel-based water heater (fuel input to hot water output)	53°C* 374 K*	Same as space heater	Same as space heater
Electrical cookers	121°C* 394 K*	Assumed constant: 80%	Assumed constant: 25%
Electrical lights and appliances	– –	Varying; assumed to be 5% on the basis of Hammond and Stapleton (2001), who took the efficiencies of incandescent lights to represent the whole category.	Varying; assumed to be 5% on the basis of Hammond and Stapleton (2001), who took the efficiencies of incandescent lights to represent the whole category.

\* Source: Reistad (1975)

<sup>+</sup> Sector-wide space heating efficiency from Utley and Shorrock (2008)<sup>‡</sup> Based on a reference temperature,  $T_0$ , of -1°C (272K; Hammond 2004b)

The conversion efficiencies summarised in Table 4-3 were used to calculate the useful energy and exergy derived from delivered fuels and electricity during the period 1970–2006, and the results are shown in Figure 4-11. The exergy and energy delivered to homes was assumed to be equal, since both fossil fuels and electricity have thermodynamic qualities of approximately one (exergy transfer = energy transfer).

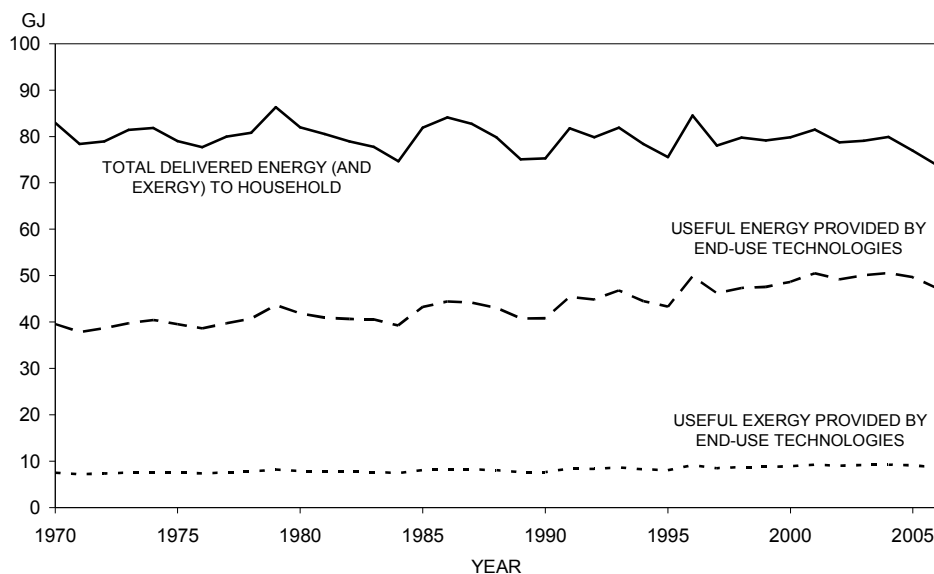
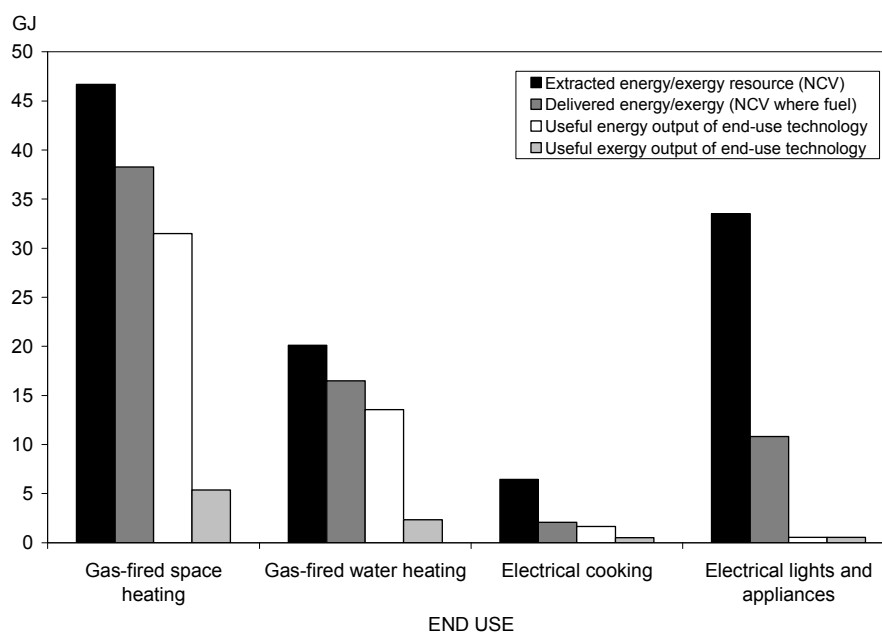
**Figure 4-11: Useful energy and useful exergy provided by end-use technologies within the average UK household, 1970–2006**

Figure 4-11 highlights that the exergy efficiency of end-use technologies is much lower than their energy efficiency. The main reason for this disparity is that a large proportion of

the high-quality energy delivered to households is used to provide low-temperature heat; a conversion achieved with a relatively high energy efficiency but low exergy efficiency.

This disparity is shown clearly in Figure 4-12, below, which disaggregates household energy use into the four end-use categories of Table 4-3. Since the majority of homes in 2006 used gas-fired central heating systems to provide both space and water heating, this has been assumed for this illustrative example. Cookers, lights, and appliances are assumed to use electricity. As well as showing conversions within the household, Figure 4-12 extends the boundary of interest upstream to show the total energy-resource requirement of each end-use category. This was achieved by multiplying delivered energy use by the average *Energy requirement for energy* (ERE) for both gas and electricity, calculated in Chapter 3.



**Figure 4-12: Useful energy and exergy derived from upstream energy flows for a representative household in 2006**

Consider, first, the space and water heating categories. Figure 4-12 highlights that the overall resource use associated with gas-fired heating is not significantly greater than the quantity of gas actually burnt in the home. It also shows that the conversion of gas into useful heat is achieved with a relatively high energy efficiency of 74%, but a low exergy efficiency of 13%. This difference is because the processes of combustion and heat transfer across a finite temperature difference are inherently exergy inefficient (as discussed Section 2.4.5; p.29). This, in turn, implies that there is a limited scope to reduce the exergy destruction associated with boiler-based space and water heating.

The inherent nature of a boiler's poor exergetic performance suggests that entirely different heating processes are required to markedly improve the situation outlined on Figure 4-12. Section 2.4.7 (p.31) introduced the idea of quality matching as an approach to help illustrate the performance of alternative options. Quality matching aims to match the

quality of the supply to the quality of the demand, and hence minimise the exergy destruction associated with a quality mismatch (a major part of the problem with using high-quality fossil fuels for low-quality heating purposes). Such a process clearly identifies heat pumps as a more exergy-effective option for space or water heating (see, for example, Nieuwlaar and Dijk 1993). An electrically-driven heat pump, for instance, uses a relatively small amount of electricity to upgrade low-quality heat from a building's surroundings to provide the slightly-higher quality heat required within a household (Leach et al. 1979), and exergy destruction is thus minimised. Of course, since such a heat pump relies on an input of electricity, the performance of the upstream supply system would also have to be included to provide a complete assessment, though that is not the objective here.

Figure 4-12 also highlights the fact that electricity is far more resource-intensive, upstream of the household, than delivered fuels. This is because most electricity is generated in large thermal power stations that suffer significant heat losses (Section 3.4). Like space and water heating, cooking is inefficient in exergy terms, since high-quality electricity is being used to provide relatively low-quality heating. A notable shortcoming of Table 4-3 and hence Figure 4-12 is the treatment of 'lights and appliances'. Both energy and exergy efficiencies were assumed to be 5% in accordance with Hammond and Stapleton (2001), who took the efficiencies of incandescent lights as representative of the whole category. In fact, as seen in Section 4.5, there are a wide variety of electricity end-uses, and these will have varying energy and exergy efficiencies depending on the application. Further work is therefore recommended to disaggregate 'lights and appliances' and find representative conversion efficiencies for end-use technologies.

In conclusion, the differing insights drawn from exergy analysis have provided alternative information regarding energy use within households. The exergy perspective has shown above that using high-quality fuels or electricity to provide low-quality heating is thermodynamically wasteful, and suggests a far greater scope for improvement than the energy efficiency of heating systems implies. Since much of the exergy destruction is inherent to the use of boilers, alternative technology is needed to significantly alter this situation, and heat pumps are among the existing options. It is recommended that further work look into the improvement potential offered by such alternative heating systems.

## 4.8 SUMMARY

This chapter has analysed the use of energy within UK households. The main objective was to provide representative electricity and hot water demands to compare with the estimated micro-generator outputs of Chapters 5 and 6. A secondary objective was to provide general context for the micro-generator assessments, since they are considered in the context of residential energy provision. In order to do this, an overview of each of the main energy end-uses has been given, some indicative daily energy-use profiles have been presented, and an illustrative exergy analysis has been carried out. Results from these sections will be discussed in Chapter 7.



## CHAPTER 5

# ANALYSIS OF A MICRO-WIND TURBINE

### 5.1 INTRODUCTION

Micro-wind for residential application is a fast-moving and emergent industry in the UK (BWEA 2009). During the early stages of the research underlying this thesis there was growing public interest in residential micro-wind turbines, predominantly for their potential to reduce the fossil-fuel use and carbon emissions associated with electricity supply. But there was a lack of information regarding their practical performance and uncertainty over their energy and carbon saving potential. This chapter and the associated publications (Allen et al. 2008a and 2008b) address this need for information. The chapter begins by reviewing some current literature regarding large- and small-scale wind turbines, before an overview of current knowledge regarding the wind resource is presented. These sections outline the need for the thermodynamic analysis of a commercially-available micro-wind turbine that is presented in Section 5.4. Results are presented with short, specific discussion, but placed in wider context within the overall discussion of Chapter 7.

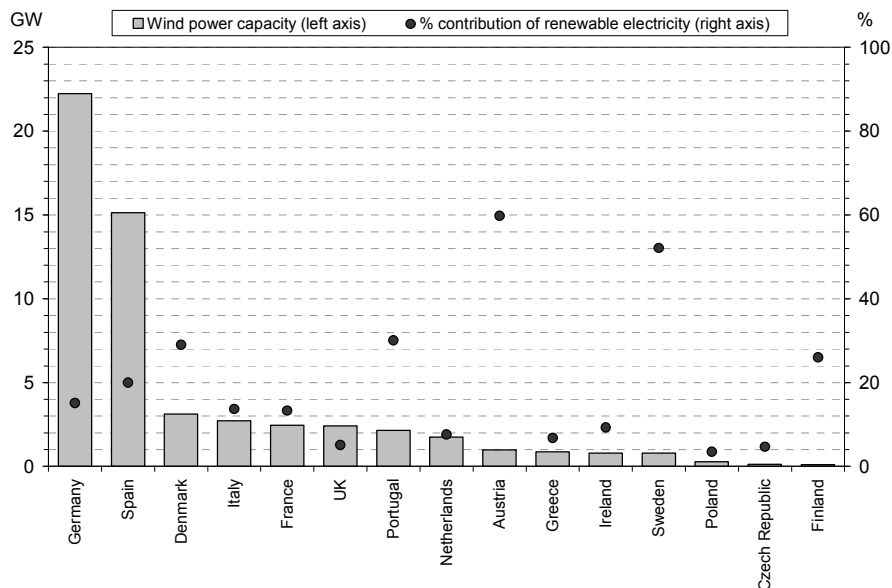
### 5.2 WIND POWER OVERVIEW

#### 5.2.1 Large-scale wind power

There has been significant growth in the global wind power industry in recent years, with an exponential take-off in capacity since the mid-1990s (Smil 2006). Wind-power capacity increased more than any other renewable electricity generation technology in 2007 (even more than hydro); an increase of 28% over 2006 with an estimated 21 GW added (REN21 2008). Wind power is also the most widely applied renewable electricity generator, with installations in over 70 countries. REN21 (2008) showed, however, that two-thirds of the global additions in 2006 were concentrated in just five countries; the U.S.A. (2.5 GW), Germany (2.2 GW), India (1.8 GW), Spain (1.6 GW), and China (1.4 GW). The UK, in comparison, added approximately 0.5 GW (BERR 2008a). The latest innovation in wind power has been the development of offshore wind turbines for shallow ocean water. Offshore wind speeds are often higher and less turbulent than onshore winds, and the planning, noise effects and visual impact are typically less restrictive for offshore turbines. Recent years have seen a few hundred megawatts added annually, mostly in Europe (REN21 2008), and many European countries have ambitious plans for large capacity increases in the near-future (Smil 2006).

In Europe, the UK has one of the best wind resources in Europe (Troen and Peterson 1989) but has only the sixth largest installed capacity of wind power (Figure 5-1). Figure 5-1 shows that in 2007 Germany and Spain had by far the largest installed capacities in Europe; 22.2 GW and 15.1 GW respectively, while Denmark, Italy, France, the UK, and Portugal had installed capacities ranging from approximately 3.1–2.1 GW. Renewable

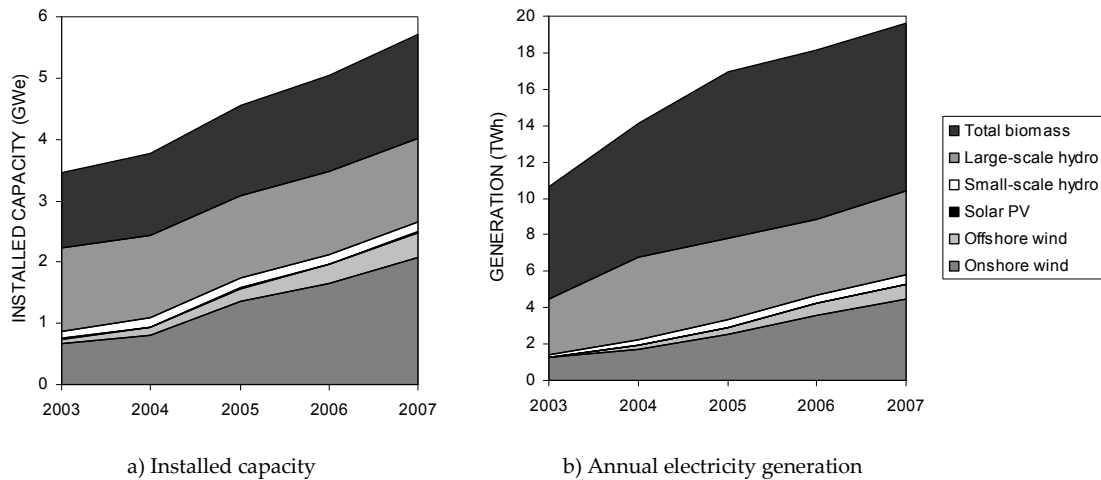
electricity in general plays a smaller part in the UK than these and many other countries, as Figure 5-1 also shows.



**Figure 5-1: Installed capacity of wind power<sup>a</sup> (left-hand axis) and % contribution of all renewables to total electricity use<sup>b</sup> (right-hand axis) in selected European countries, 2007**

Source: a) EWEA 2009b; b) Eurostat 2009

The UK generates just under 5% of its electricity with renewable sources (the dark grey dot on Figure 5-1). Of these sources, large-scale wind turbines represent a significant proportion of installed capacity (Figure 5-2a; onshore and offshore wind). However, since wind turbine capacity factors are lower than some other renewable generators (notably biomass and large-scale hydro), the proportion of generation from wind is less than their capacity proportion (Figure 5-2b). Wind capacity grew from 0.74 GW in 2003 to 2.5 GW in 2007 (44% of renewable capacity in 2007), while annual electricity generation rose from 1.3 TWh to 4.5 TWh (27% of renewable electricity generation in 2007).

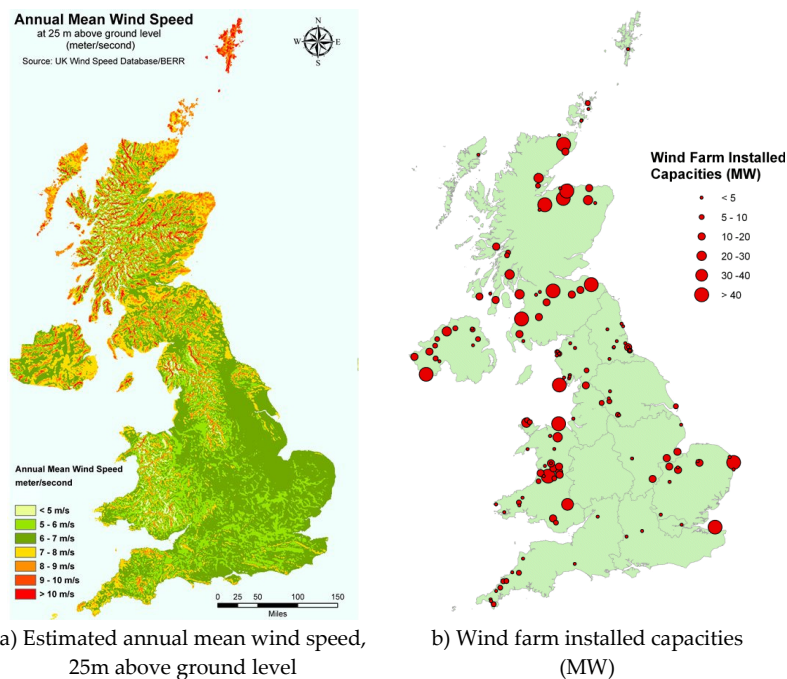


**Figure 5-2: Capacity of, and electricity from, renewable sources, 2003–2007**  
(Source: BERR 2008a Table 7.4)

Figure notes

- 'Large-scale hydro' excludes pumped storage
- 'Biomass' includes landfill gas, sewage sludge digestion, municipal solid waste, and animal and plant biomass.

Figure 5-2 shows that the majority of wind-generated electricity currently comes from onshore turbines, with offshore turbines taking a minor role. The wind resource on-land is generally preferable in the west and north of the UK (Figure 5-3a), and the majority of the installed large-scale onshore capacity is situated accordingly (Figure 5-3b). This contributes to the current situation of significant north-south power flow experienced by the British electricity network (Strbac 2008). The UK's offshore potential is vast, and by January 2009 the UK had the largest capacity of offshore wind power in Europe; 0.59 GW or 39% of the European total, with a number of further offshore wind farms under construction or in planning (EWEA 2009a).



**Figure 5-3: UK wind resource and geographical location of wind farms**  
(Source: RESTATS 2007)



Although global growth in wind power is strong there is still a large gap between the current contribution that renewable electricity generation makes in the UK and the national targets. A 2001 EU Directive set a target of 12% of energy (22.1% of electricity) from renewable generation by 2010, with a UK 'share' of 10% of UK electricity consumption by this date (BERR 2008a). In 2007, 4.9% of electricity came from renewable generation, up only 0.44% during 2006–2007 and 0.29% during 2005–2006 (*ibid*). Given this rate of progress, the EU's UK target for 2010 is unlikely to be reached. More recently, in March 2007, the European Council established a target of 20% of the EU's energy to come from renewable sources by 2020, and in January 2008 the Commission proposed that the UK provides 15% of its total energy use (i.e. electricity and fuels used) with renewable sources by 2020. On the Eurostat accounting basis, the UK provided 1.78% of final energy used with renewable sources in 2007 (*ibid*) and so again, a significant challenge remains if renewable energy supply is to increase to target levels.

### 5.2.2 Net energy and carbon performance of large-scale wind

Major drivers underlying targets for renewable energy provision are the desire to reduce greenhouse gas emissions and provide energy security (BERR 2008j) by reducing use of and dependence upon fossil fuels. In order for renewable energy technologies to perform well in these terms, they must supply enough energy during their operation to outweigh their energy-resource requirements (since these are mainly fossil fuels in many countries) and the carbon emissions associated with their life cycles. Net energy and carbon analyses can contribute to answering these questions.

Previous research has indicated that medium and large-scale wind turbines perform well in net energy terms. Lenzen and Munksgaard (2002) examined more than 70 published studies of predominantly medium and large-scale wind turbines, and although there was a large range and scatter in the results they found good energy and carbon performance relative to fossil-fuel based technologies. After normalisation with respect to operational lifetime and capacity factor (to 20 years and 25% respectively), the wind turbines were found to require between 0.014 to 0.15 units of primary energy per unit of electrical output ( $\text{MJ}_{\text{primary}}/\text{MJ}_{\text{electricity}}$ ) over the lifetime of the device, with a mean of 0.062. These 'Energy requirement for energy' (ERE) values are significantly lower than those of UK fossil-fuel power stations (see Table 3-4, p.52). In the mean case, a turbine would generate a quantity of electricity equal to its primary energy requirement in 1.24 years (0.062 multiplied by 20 years) or 14.9 months. This is the simple energy payback period (EPP) as discussed in Section 2.3.7.5 (p.21). Lenzen and Munksgaard (2002) calculated the mean 'displaced EPP' (see again Section 2.3.7.5) by assuming a conversion efficiency of 35% (fossil fuel to electricity) for the 'conventional power plants' that would be displaced by a wind turbine, which means each unit of electricity from the turbine displaces 2.9 units of fossil fuel and the displaced payback time is therefore 5.2 months. The minimum and maximum displaced EPPs, corresponding to the minimum and maximum EREs of 0.014 and 0.15  $\text{MJ}_{\text{primary}}/\text{MJ}_{\text{electricity}}$ , are 1.2 and 12.6 months. Thus, it is likely that within a few months, and almost certainly within a year, the turbines would displace enough fossil fuel (given the conventional power plants assumed by Lenzen and Munksgaard) to break even

with their energy investment, and therefore provide 'free' electricity for the remainder of their expected 20 year lifetimes.

Other studies of large wind turbines agree with the findings of Lenzen and Munksgaard (2002). Figures published by Krohn (1997), for example, indicate that the ERE of a modern Danish 600kW is approximately  $0.03\text{--}0.04 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{electricity}}$ , and Krohn calculated a displaced energy payback period of 3.3–4.1 months (when displacing a new coal-fired power station). Martínez et al. (2009) indicate that a modern 2 MW (80m diameter) turbine has an ERE of approximately  $0.02 \text{ MJ}_{\text{primary}}/\text{MJ}_{\text{electricity}}$  and a simple payback period of 4.8 months (they did not estimate a displaced payback period, but this would of course be an even smaller time-period).

By displacing fossil fuel generators, wind turbines can reduce the carbon emissions associated with electricity supply. The life-cycle CO<sub>2</sub> emissions associated with the turbines in Lenzen and Munksgaard's review had a wide range – 7.9 to 123.7 gCO<sub>2</sub>/kWh not including transmission/distribution losses – but are nevertheless significantly lower than fossil-fuel based electricity. For example, both the system average and marginal emissions factors of the UK grid are above 500 gCO<sub>2</sub>/kWh (Section 3.4.6; p.53). Wind turbines do not directly replace conventional fuel-based methods of electricity generation, since wind-based electricity has very different characteristics to fuel-based electricity, but nevertheless the significant difference in the figures suggest wind power can indeed reduce carbon emissions.

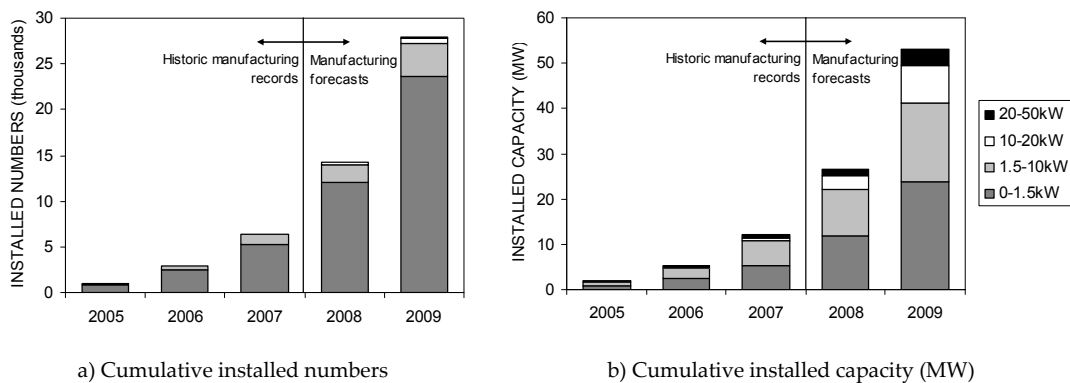
There are difficulties associated with comparing the results of different energy (or carbon) analyses. Lenzen and Munksgaard (2002) identified discrepancies in: 1) values for the energy content of materials; 2) the analysis scope, or breadth; 3) the methodology, or analysis depth. Further than these procedural issues, they found that the figures are influenced by: 4) the country of manufacture; 5) recycling or overhaul of components after the service life (which is also treated differently by different methodological accounting procedures employed); and 6) the choice of concrete or steel for the tower. In addition to these parameters, the carbon-emission factors also vary according to the fuel mix in the country of manufacture. Nevertheless, the scatter of Lenzen and Munksgaard's net energy and carbon results are significantly lower than fossil-fuel based generation technologies, and hence these differences do not change the general conclusion.

### 5.2.3 Small-scale wind turbines in the UK

Development of large-scale wind power is strong and relatively well established (at least across Europe as a whole; EWEA 2009b) and appears justified in energy and carbon terms. Small-scale wind for residential electricity generation, in contrast, is at an emergent stage – both in the UK and in other countries – and its relative performance is less certain.

The British Wind Energy Association (BWEA) recently estimated that in 2007 there were a total of approximately 6410 small- and micro-wind turbines installed in the UK, on the basis of historic manufacturing records (BWEA 2008a). These were mainly turbines with a rated power of less than 1.5 kW, which accounted for 82% of the total number of

turbines (Figure 5-4a). Although installed in smaller numbers, 1.5–10kW turbines contributed the largest proportion toward total rated capacity due to their larger size, and accounted for 46% of the total in 2007 (Figure 5-4b). If manufacturing forecasts turn out to be correct, 2008 and 2009 will see or have seen strong growth in the industry. Installed numbers will still be small, however, relative to the numbers of households – the forecast for 2009 would mean that approximately 1% of the housing stock would then have small wind turbines.



**Figure 5-4: Small- and micro-wind turbines in the UK**

The geographical spread of small-scale wind turbines is much broader than that of large-scale wind; contrast Figure 5-5 with Figure 5-3b. While large wind turbines are typically owned by energy companies and installed as wind farms in generally clear, open spaces on high ground, small wind turbines are typically owned by householders spread all over the UK.



**Figure 5-5: Geographical location of small and micro wind turbines**

(White dots: turbines < 5 kW<sub>p</sub>, red dots: turbines > 5 kW<sub>p</sub> and < 10 kW<sub>p</sub>. Source: Sissons et al. (2008)

#### 5.2.4 Net energy and carbon performance of small wind turbines

There is currently little published empirical data concerning the electricity output of small wind turbines. While the electricity outputs of large wind turbines are logged and recorded for commercial purposes, they are not yet typically recorded in the case of small wind turbines. Electricity outputs are a significant determinant of net energy and carbon performance, which also lack published information.

It may be that the net energy performance of small and micro-wind turbines is poorer than that of their larger counterparts. Lenzen and Munksgaard (2002) identified economies of scale in energy performance; the larger the turbine, the better the net energy performance. This indicates that the increased output of larger turbines outweighs their increased energy requirements. However, there were only a few small turbines in Lenzen and Munksgaard's sample. The majority of turbines examined were of medium and large-scale turbines; diameters of 20m to as much as 100m and rated power outputs of the order of hundreds or even thousands of kilo-watts. Only 20% of the reviewed studies were of turbines falling within the UK's definition of 'micro-generation' – less than 50 kW<sub>e</sub> in the case of electricity generation (Section 1.2) – and only a couple of turbines were at the smallest scale of 'micro-wind'. 'Micro-wind' is defined here in accordance with the British Wind Energy Association's definition (BWEA 2008a), as having a rotor diameter of less than 2.1m or swept area of 3.5m<sup>2</sup>, while 'small wind' refers to turbines larger than this but with rated capacities below 50 kW<sub>e</sub>.

A small number of recent net energy and carbon analyses of small and micro-wind turbines do exist. Rankine et al. (2006) calculated the life-cycle energy requirements and carbon emissions of the 'Swift' micro-wind turbine; a commercially-available horizontal-axis machine with a diameter of 2m, a rated power of 1.5 kW at 12 m/s, and an estimated lifetime of 20 years. They assumed that the grid-connected turbine would displace primary energy and associated carbon emissions from the established UK grid, and used a 'system-average' ERE and carbon-emission factor (Section 3.4.6) in order to calculate this displacement. For an assumed (i.e. not estimated nor measured) annual output of 1000–4000 kWh the displaced energy payback time was 6.2–1.5 years while the carbon payback time was 4.8–1.2 years. These outputs represent capacity factors of 8–31% and Rankine et al. estimated that they correspond to annual mean wind speeds of approximately 4.0–7.2 m/s. Rankine et al. found that the predominant source of embodied energy and carbon was the aluminium that constitutes a considerable proportion of the design. They estimated that if extruded recycled aluminium replaced virgin aluminium in the design, the displaced energy payback period would reduce by two-thirds and the carbon payback by one-third.

Celik et al. (2007) used wind speed data from five urban sites in Turkey to estimate the energy output of a small HAWT of 9m diameter with a tower height of 24m (this is very large for individual household application, but suitable for community application). They estimated the embodied energy and carbon of the turbine when operating with a generator of rated power 22.5 kW, and calculated that, when displacing a 'conservative European average electricity mix', the turbine would have a displaced energy payback period of 1.4

years and carbon payback period of 0.7 years in the site of best wind resource. This site had an annual mean wind speed of 4.9 m/s (at a height of 10m) with a highest monthly mean of 8.1 m/s in August. For the site with the smallest wind resource (annual mean wind speed = 2.6 m/s), these figures translate to 13.7 years and 8.2 years respectively.

These studies give a tentative corroboration of Lenzen and Munksgaard's 'bigger is better' conclusion. Indicative payback times of large turbines were within a year – often within only a few months – whereas even the shortest payback times of small wind were more than a year (although recycled material inputs could reduce this). Nevertheless, given the average wind speeds outlined the payback times of a year or so are still very short relative to expected lifetimes of 15–20 years, and hence it appears that small and micro-wind turbines can perform well in both net energy and carbon terms when displacing current (fuel-based) electricity generation techniques. These studies are a very small sample, however, and this lack of evidence was a major driver for the research underlying this chapter and the wider research this work contributed to (Allen et al. 2008b).

### 5.2.5 Electricity outputs of small wind turbines in the UK

The energy and carbon payback times of wind turbines are sensitive to annual electricity output, which in turn is sensitive to the wind resource. The majority of the UK's population lives in built-up areas – approximately 90% within the U.N.'s definition of 'urban' (Appendix A) – and there has therefore been significant interest in the application of micro-wind turbines to the built environment. The wind resource in such environments is, however, complex, and its suitability for wind turbines is uncertain, an issue compounded by the lack of empirical evidence of performance. Indeed while Bahaj et al. (2007) suggested that micro-wind turbines could have a promising future in coastal or high inland sites, they considered it unlikely that such turbines would proliferate in urban or suburban environments.

At the time of writing, one small urban field trial (the 'Warwick Microwind Trial') had recently published data from 26 building-mounted horizontal-axis wind turbines from five UK manufacturers (Encraft 2009). This gives an early indication that mounting such turbines upon average households in urban environments is unlikely to provide useful electricity outputs, although mounting upon tall exposed buildings was more successful. While insightful to a certain extent, this is a very small data sample and hence further work and trial data is required in this area. The forthcoming results of a larger field trial supported by the Energy Saving Trust (Sissons et al. 2008), which is due to report at approximately the end of April 2009 (P.A. James, Southampton University, 2009, personal communication), will provide useful further evidence.

Although early indications are that typical urban households are unsuitable micro-wind turbine locations, there may well still be scope for urban wind turbines. Buildings can create pressure differentials that accelerate flow and thus offer the potential for power production from a suitably integrated wind turbine. Mertens et al. (2003), for example, showed that the skewed flow occurring above tall, flat roofed buildings increased the

power output of a prototype vertical-axis wind turbine (VAWT), compared with non-skewed flow. Van Bussel and Mertens (2005) suggested that VAWTs do not suffer during frequent wind-direction changes as much as horizontal-axis wind turbines (HAWTs; which have to yaw in order to align their rotors with the wind), and therefore VAWTs may be preferable in turbulent, urban environments. Furthermore, they indicate that the use of existing small wind turbine designs (i.e. HAWTs) that were not originally designed for the built environment will be problematic, since additional urban requirements include severe noise restrictions and the ability to match the structural and aesthetic integrity of buildings. Van Bussel and Mertens were thus involved in the development of the 'Turby', a small VAWT designed explicitly for building integration. Field trial data is currently lacking however, to corroborate the claims of better VAWT performance, although a field trial underway at the time of writing in Zeeland in the Netherlands, which includes the 'Turby', will improve this situation. In the UK, a similar vertical-axis wind turbine (the 'quietrevolution') appears to have a promising future, since the manufacturer has recently received a significant (£6 million) investment from a German energy company to develop its design further (Mortishead 2008). A further alternative building-augmented wind turbine is the 'ducted wind turbine' investigated by Dannecker and Grant (2002). They suggest that ducted wind turbines can benefit from accelerated flow resulting around a building, although again, full-scale performance tests are required to corroborate this.

### 5.2.6 Summary

Much of the interest in renewable electricity generators such as wind turbines is driven by the desire to decarbonise electricity supply and increase energy security by reducing the use of, and dependence upon, fossil fuels. Accordingly, significant targets for renewable energy provision have been set.

Growth in the relatively established large-scale wind industry appears justified in net energy and carbon terms. Literature indicates that medium and large-scale turbines, which have expected lifetimes of 20 years or so, pay back their embodied energy and carbon in a few months (and almost certainly within a year) when displacing fossil-fuel based generation. There is relatively little net energy and carbon data, however, concerning the emergent small-wind industry. Data is lacking both in terms of embodied energy/carbon data and, significantly, in terms of typical electricity outputs in different residential environments. The more established part of the small-wind industry is that of horizontal-axis wind turbines (HAWTs), and there is great interest in using them for household electricity generation.

There is therefore a need for further research on the energy and carbon performance of small wind turbines. This chapter aims to add to the evidence-base through the study of a micro-HAWT for residential electricity provision. The chapter now proceeds with the theory of power production with wind turbines and a brief overview of current knowledge regarding the wind resource. This underpins the analysis of a commercially-available micro-HAWT presented in Section 5.4.

### 5.3 WIND TURBINES AND THE WIND RESOURCE

#### 5.3.1 The power in the wind

The gross instantaneous power of the wind,  $P_G$ , may be determined as follows:

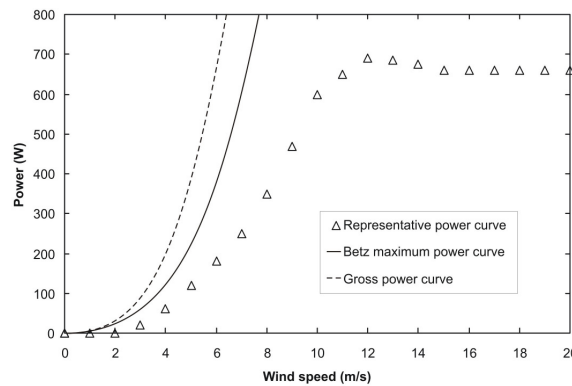
$$P_G = \frac{1}{2} \rho A u^3 \quad 5-1$$

where  $\rho$  is the density of air,  $A$  is the cross-sectional area the air is passing through, and  $u$  is the perpendicular wind speed in metres per second (Sahin et al. 2006).

The power available is thus most sensitive to wind velocity via a cubic relationship: if the speed is doubled, the available power is increased eightfold. It is therefore important to situate a wind turbine in the best possible wind regime since high wind speeds are significantly more powerful. Also significant, but less so than wind speed, is the effect of turbine diameter. The power available is directly proportional to the swept area and thus to the square of the turbine diameter (for a horizontal-axis wind turbine). Doubling the diameter quadruples the power available. The density of air further affects the available power, and this too can have an important affect (Gipe 2004). It is a function of the air pressure and temperature, both of which vary with altitude and broad meteorological conditions.

#### 5.3.2 Power capture with a wind turbine

Betz (1946 in Sahin et al. 2006) established that the maximum power that can be extracted from the wind is 59% of the gross power  $P_G$ . In practice, due to aerodynamic and power conversion losses, turbines extract less than the Betz limit. Power curves are often used to communicate the power generation capabilities of a turbine with varying wind speed. Figure 5-6 shows a representative micro-wind turbine power curve, compared with the gross power available and that available according to the Betz law. The power curve indicates that the turbine will capture less than available according to the Betz limit, for a given wind speed, which in turn is less the gross power available.



**Figure 5-6: Representative power curve for a micro-wind turbine compared with gross power available and the Betz limit**

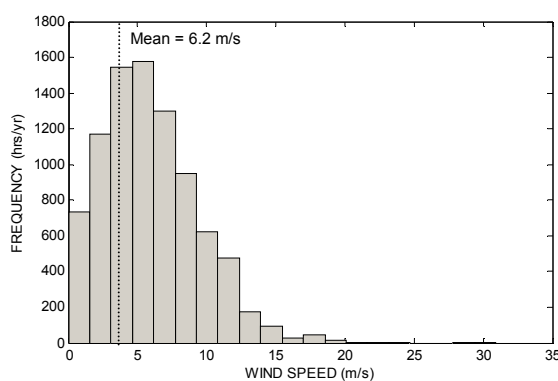
(Sources: manufacturer's data sheet; Betz 1946 in Sahin et al. 2006)

In general, micro-wind power curves can be categorised by three general stages. Below the cut-in speed (in this case, 2 m/s) the wind is insufficient to operate the turbine. Between cut-in and the peak power output the curve is approximately cubic, and finally in the post-peak stage micro-wind power curves level-off (as in the case of Figure 5-6), decrease, or cut out completely, through a variety of safety measures.

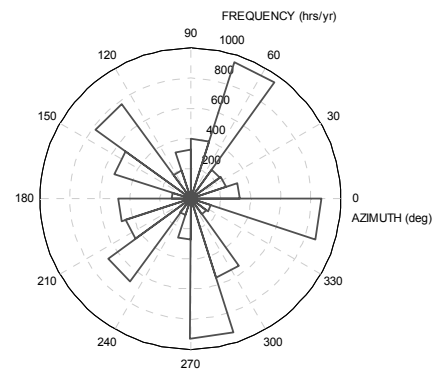
Small- and micro-wind turbine power curves have been the subject of controversy in recent years. This has been due to a lack of independent corroboration of manufacturer's published curves, compounded by the variety of ways in which manufacturers calculate and produce them. For example, the power curve should represent net power output to the load, after any parasitic losses from inter-connection components (BSI 2006c), but it may instead represent the gross power output of the generator prior to such losses (Gipe 2004). In addition, if a power curve is based on the idealised conditions of wind tunnel test facilities it is unlikely to be representative of performance in the more turbulent structure of real winds. Further work is required in this area to enable an improved understanding of turbine performance and fairer comparisons between small wind turbines. The publication of the recent British Wind Energy Association's 'Small wind performance and safety standard' (BWEA 2008b), which requires adherence to the relevant British Standard for power curves (BSI 2006c), is likely to improve the situation, but at the time of writing (early 2009) it had not been implemented evenly across the micro-wind industry.

### 5.3.3 Wind resource assessments

Knowledge of the power producing capability of a wind turbine enables an estimate of an energy output given an assessment of the wind resource. Wind speeds at a given site vary continuously throughout the year and often have distinct patterns of monthly and daily variability (Sinden 2007), and they are typically more frequent at lower speeds whereas high wind speeds are relatively rare (Gipe 2004). Figure 5-7a gives an example of a wind resource recorded in Avonmouth near Bristol in 1990, where the dominance of relatively low wind speeds is clear. It is also common for the wind to be dominant from certain directions, which can affect the appropriate location of a turbine. This can be communicated with a 'wind rose', an example of which is given in Figure 5-7b.



a) Histogram of hourly average winds speeds



b) Wind rose of hourly average direction

**Figure 5-7: The wind resource at Avonmouth Weather Station, Bristol, 1990**

(Source: Met Office 2006b)



Since the power available is proportional to the cube of the wind speed, high wind speeds account for a disproportionately high amount of the power available. (Put another way: the average of the cube of a sample of wind speeds is greater than the cube of the average speed.) For this reason an annual mean wind speed, on its own, is an insufficient measure of the wind resource. While a measured dataset of wind speeds at the prospective site over an extensive period (e.g. at least one year) provides the most preferable assessment, a statistical distribution can (in some cases) be used with an annual mean from a wind atlas to give an initial resource assessment.

The Weibull frequency distribution is a two-parameter probability density function that has been shown to give a good fit to such measured wind speed data (Justus et al. 1976; Seguro and Lambert 2000; Gipe 2004). Chadee and Sharma (2001, in Met Office 2008) note, however, that no single distribution could be expected to give good results in all situations. They describe five 3-parameter distributions that they believe merit further investigation. Kantar and Usta (2008) proposed a ‘minimum cross entropy’ distribution, and found that it provided a better fit to a variety of measured wind speed data than the Weibull distribution. Nevertheless, the Weibull distribution is flexible and generally applicable, and for these reasons it has been widely adopted by the wind energy community (Chadee and Sharma 2001, in Met Office 2008).

Sources that provide estimates of annual mean wind speeds for the UK include BERR’s ‘NOABL’ database (BERR 2006) and the Danish Risø National Laboratory’s ‘European Wind Atlas’ (Troen and Peterson 1989). In situations of sufficiently homogenous and smooth landscape, these annual mean wind speeds may be adjusted to different heights through use of a parameter relating to the ‘roughness’ of the surface, and then combined with a Weibull distribution in order to estimate the wind resource. For many instances of prospective small wind installations, however, the location is complex and the landscape heterogeneous and relatively rough, and this approach is therefore problematic and unlikely to give a true representation of the resource. Further discussion of the structure of the wind is now therefore required, particularly that close to the ground in heterogeneous areas such as urban environments.

### 5.3.4 Understanding the wind

#### 5.3.4.1 Layers in the atmosphere

The atmosphere can be represented by a number of distinct but interdependent layers. At the global scale, up in the *free atmosphere*, *geostrophic winds* are caused by pressure gradients that are generated by the differential heating of the Earth’s surface by the Sun, and are further affected by the Earth’s rotational motion (the Coriolis effect). Nearer the surface, within the *boundary layer*, winds are driven by, and vary with, geostrophic winds, but the details of the wind profile depend upon the strength of turbulent mixing that is influenced by localised thermal and mechanical effects (Gandrilie et al. 1988; Met Office 2008).

Heating at the surface, for example in the afternoon, causes the formation of thermals and strong turbulent mixing. This produces a convective boundary layer exhibiting a

mean wind that is constant throughout most of its depth and has strong shear close to the surface (Met Office 2008). Conversely, cooling at the surface, during the night, damps turbulence and produces a stable boundary layer that exhibits significant wind shear throughout its depth (*ibid*). The result is a typically diurnal cycle in near-surface winds. Sinden (2007) demonstrated this during an analysis of long-term wind patterns from wind observations across the UK, by showing a clear pattern of higher wind speeds during daylight hours, particularly in the afternoon, in comparison to overnight. The diurnal effect is more pronounced in summer months when daytime heating is strongest. In contrast, the diurnal differences during winter are smaller while winds are generally stronger at all times of the day. Sea breezes are also driven by local temperature differences and are diurnal in nature (Danish Wind Energy Association 2003). Land masses are heated more quickly than the sea during the day, causing thermals that create low pressure and draw cool air from the sea. At nightfall there is often a period of calm as land and sea temperatures equalise, before winds turn seaward as the daytime temperature difference reverses (although the difference is usually of smaller magnitude). These local effects typically cause higher wind speeds in coastal areas than inland areas.

In near-neutral conditions (when heating or cooling of the atmosphere from the surface is insignificant), turbulence is largely mechanically driven (Met Office 2008). Mechanical effects include those caused by friction and topography. Friction causes drag at the surface that reduces the speed of the wind close to the ground, and its magnitude depends upon texture of the surface. *Roughness elements* such as hedgerows, trees and buildings together form the *canopy*. The *roughness length* is a parameter that characterises the roughness of homogenous (uniform) surfaces: the higher the roughness length, the rougher the surface. Roughness elements interact directly with the wind through the pressure exerted on them by the wind, and the drag is thus transmitted to wind at higher elevations by the action of turbulent stresses (*ibid*). The result is a reduction of wind speed with decreasing height, implying that elevated wind turbines will perform preferably to those installed close to the ground. As well as generally increasing with height above ground, wind speed is affected by the shape of the land (topography). For example, winds typically speed up over hills. However, such effects are generally less relevant to small wind turbines, due to their likely proximity to buildings in low-lying land (The Carbon Trust 2008).

While this qualitative understanding of the behaviour of the boundary layer is good, the quantification of low-level winds is more problematic, particularly in complex environments such as urban areas. Further discussion of the current understanding of the boundary layer is now, therefore, presented.

#### 5.3.4.2 Understanding the boundary layer

The boundary layer can generally be characterised by a number of interdependent sub-layers: the inertial sub-layer; the roughness sub-layer; and the canopy sub-layer.

The *inertial sub-layer* is the region in which the height scale is much greater than the mean height of the canopy, but much less than the depth of the boundary layer. Within the inertial sub-layer the effect of mechanical drag on the wind profile may be represented by a logarithmic relationship derived from a theoretical understanding of the physics involved (Met Office 2008). In certain situations, an alternative, empirically-determined power law profile is also applicable (*ibid*). If the surface roughness length is large the logarithmic profile can be adjusted by a displacement height that quantifies flow-blocking effects and adjusts the effective origin from which height is measured (Heath et al. 2007; Met Office 2008). In this case, the semi-log profile gives the variation of the mean horizontal wind speed with height,  $z$ , as follows:

$$u(z) = \frac{u_*}{\kappa} \ln \left( \frac{z-d}{z_0} \right) \quad 5-2$$

where  $u_*$  is the *friction velocity* and is equal to the square root of the turbulent shear stress divided by the air density, while  $\kappa$  is a constant of proportionality ('Von Karman's constant'; approximately equal to 0.4), and  $z_0$  and  $d$  are the *roughness length* and the *displacement height*, respectively. Rougher surfaces create greater drag and are represented by larger roughness lengths, affecting the wind speed at all heights.

The log profile can be corrected for the turbulent mixing caused by surface heating or cooling (discussed in Section 5.3.4.1), yielding the *stability-corrected logarithmic wind profile* (Met Office 2008). These formulae do not attempt to predict flow at a given point (Heath et al. 2007). Rather, they give an average speed over a homogenous area of a few hundred metres, given a known or estimated roughness length and displacement height. This is, of course, problematic for estimating the wind resource at a specific prospective turbine site, particularly when the environment is heterogeneous.

Below the inertial sub-layer is the *roughness sub-layer*. In urban environments, interacting wakes and plumes of heat, humidity, and pollutants are introduced by individual roughness elements (Arnfield 2003). The height of the roughness sub-layer has been a subject of much debate. For urban environments, Roth (2000) proposed that it has dimensions of the order of tens of metres and extends to about 2.5 to 3 times the average height of the buildings. The turbulence field within this layer is often not horizontally uniform, even on a time average, and must be considered three-dimensional (*ibid*). Flow within the roughness sub-layer is thus more complex than that in the inertial sub-layer, and it is more complex still below the average height of the canopy (e.g. the average height of buildings) within the *canopy sub-layer*. The horizontally averaged wind profile in the roughness sub-layer tends to have a maximum in the wind shear – an inflection point in

the wind profile – at the top of the canopy, with a quasi-exponential decay of wind speed with height towards the ground (Met Office 2008).

#### 5.3.4.3 *Modelling the wind near households*

The estimation of the wind resource within an environment of significant roughness (e.g. an urban environment) is difficult even where it is uniform (homogeneous). Nevertheless, modern modelling techniques are increasing understanding of flow characteristics for certain idealised building configurations such as street canyons, isolated buildings and uniform arrays of buildings, and providing some useful general guidance (*ibid*).

Heath et al. (2007), for example, developed a computational fluid dynamics (CFD) model to simulate flow across and around a staggered array of similar pitched-roofed households, for which they modelled the inflowing wind using the semi-log profile given in Equation 5-2. On this basis, they developed a case study of a house in a hypothetical homogenous area of west London. While they stated that the numerical results must be considered as ‘very approximate’ and applicable only to building arrangements similar to that modelled, it was possible to draw some general conclusions. They found that mean modelled wind speeds were much lower than those suggested by the NOABL mass-consistent model (BERR 2006), and hence indicated that the NOABL wind atlas should be used with (extreme) caution. They also found that, because the wind is sheared strongly at the rooftop, the output of a turbine would be extremely sensitive to mounting height, which indicates that planning permission allowing installation above the rooftop ridgeline will be important for reasonable electricity outputs. Furthermore, even when mounted above the ridge, the calculations indicated that the output of a turbine mounted upon the roof of an average urban household is likely to be low.

#### 5.3.4.4 *Measuring the wind resource*

While modelling work is increasing understanding of flow near and around households, accurate predictions of wind profiles remain difficult; especially near the top of canopies (Met Office 2008). Furthermore, modelling is not yet feasible for the heterogeneous environments typical of real-world situations involving households. Even many rural environments will have heterogeneous characteristics such as non-uniformly arranged trees, hedges, and buildings within close enough proximity of a prospective site to cause problems for wind resource estimation. The direct measurement of wind speeds is therefore likely to remain necessary when considering a prospective residential wind turbine site. Indeed, the Carbon Trust’s ‘Wind Yield Estimation Tool’, recently developed in collaboration with the Met Office, recommends that if its estimation indicates a potentially good location, the user should then conduct ‘an extensive period of anemometer testing at the installation location and hub height of the proposed turbine’ (Carbon Trust 2009). Such testing is becoming more feasible for householders as low-cost wind sensors are becoming available (e.g. an anemometer with PC logging kit for £65; Better Generation 2008).

### 5.3.5 Summary

The power available in the wind is proportional to the cube of the wind speed and, in the case of a horizontal-axis turbine, the square of the turbine diameter. The electricity outputs of wind turbines are therefore particularly sensitive to wind speed and turbine diameter.

The wind is a complex phenomenon. It is understood relatively well in a qualitative sense, and also in a quantitative sense in certain simple situations involving homogenous, smooth surfaces. In such situations a logarithmic (or power law) profile can be used in conjunction with an estimated 'roughness length' and a mean annual wind speed at a specified location, available from wind atlases (e.g. BERR 2006 and Troen and Peterson 1989). An appropriately-adjusted annual mean can then be combined with a statistical wind speed distribution and the power curve of the turbine to give an initial indication of the electricity-generation potential of the location. This approach is often invalid, however, in residential areas and certainly in urban areas, due to their complexity and significant 'roughness'.

Modern modelling techniques are providing some general insights into the behaviour of the wind in rough but homogenous terrains including, for example, a quantitative indication of the importance of installation above the ridgeline of households. But the direct measurement of wind speeds at prospective sites is generally still necessary to enable a wind resource assessment at a specific site, and is therefore recommended.

## 5.4 THERMODYNAMIC ANALYSIS OF A MICRO-WIND TURBINE

### 5.4.1 Introduction

Section 5.2 showed that current evidence regarding the net energy and carbon performance of small wind turbines is lacking, partly because their electricity output capabilities are uncertain for residential areas. Section 5.3 then indicated that, ideally, measured wind speeds should be used to estimate the electricity output of residential micro-wind turbines. The following analysis of a commercially-available micro-wind turbine therefore uses a dataset of measured wind speeds to estimate electricity outputs, and then uses this information to estimate the turbine's net energy and carbon performance. Outputs are also put into context through comparison with representative household electricity demands.

### 5.4.2 Background to the research

The research reported here forms part of a wider integrated appraisal, which was conducted in collaboration with a UK micro-wind manufacturer. The collaboration provided vital real-world data for the appraisal process, particularly in the form of an inventory of construction materials and production processes. This enabled an estimation of the turbine's embodied energy and carbon – an important part of the net energy and carbon analysis presented in Section 0. Earlier forms of the work reported here were published by Allen et al. (2008a and 2008b).

### 5.4.3 The micro-wind turbine

The micro-wind turbine examined in this section is a commercially-available horizontal axis wind turbine (HAWT) with a rotor diameter of 1.7 m, a rated power of 600 W at 12 m/s, and an assumed lifetime of 15 years. The assumed installation configuration is outlined in Figure 5-8. The turbine considered here is used in conjunction with a permanent magnet, brushless generator that generates varying frequency, varying voltage three-phase AC. A rectifier then converts this to varying voltage DC, prior to inversion to grid-compatible AC (fixed-frequency, fixed-voltage, single-phase).

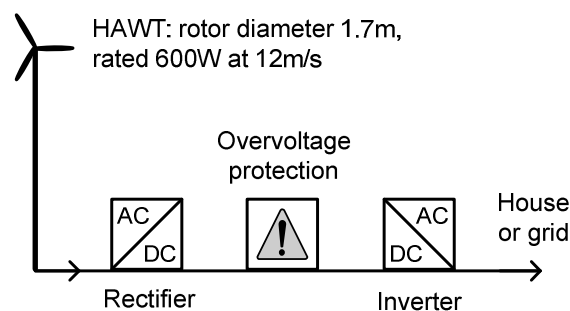


Figure 5-8: Installation schematic of the micro-wind turbine

## 5.4.4 Methodology

### 5.4.4.1 Overview

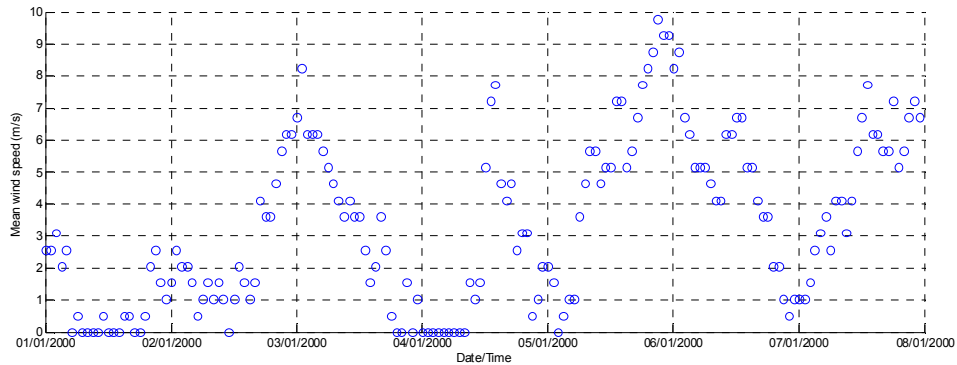
An overview of the electricity-output estimation methodology is now presented, prior to greater detail regarding each element. In the subsequent results section the estimations are discussed, and the embodied energy and carbon values are brought in (from the collaborative life cycle assessment) to enable a net energy and carbon assessment.

A dataset of hourly mean wind speeds were used to estimate the electricity output of the micro-wind turbine represented schematically in Figure 5-8. Programs were written and executed in MATLAB (The MathWorks 2007) to extract and filter Met Office wind speed data from a variety of locations over the period 1990–2006, and to use these data to estimate the annual electricity output of the turbine in each location. The gross power output of the turbine was estimated by reference to the turbine's power curve. This was integrated over the hour to give an energy output and altered by a variety of factors to determine the net electricity delivered to the household or grid. These factors were the estimated turbulence intensity of the wind at the location in question, the annual availability of the turbine (allowing for maintenance/breakdown), and an air density adjustment factor, all discussed below. Finally, the hourly electricity outputs were summed to provide annual values, and normalised against a standard year of 8760 hours. While the approach was applied to a dataset of wind speeds selected from the Met Office's 'Land Surface Observation Stations Data', which is available to researchers via the British Atmospheric Data Centre (Met Office 2006c), it could equally be applied to any collated dataset of wind speeds. Similarly, while the methodology was applied to examine only one specific, commercially-available micro-wind turbine, other power curves and inverter characteristics could be used to estimate the outputs of different turbines. Each key element considered within the methodology is now outlined in further detail, before being summarised together with the final estimation algorithm in Section 5.4.4.8.

### 5.4.4.2 Wind speed data

A dataset of hourly-average wind speeds was selected from the Met Office's 'Land Surface Observation Stations Data' (Met Office 2006d). Data from a total of twenty-six weather stations across the UK were chosen for the period 1990–2006 on the basis of the following selection criteria. The use of a long dataset is preferable because the wind resource can vary year-to-year (Sinden 2007), and so dataset length was a key factor during selection. Other key criteria were geographical location (to give broad coverage across the UK) and terrain type ('open' and 'urban' – see below). Both were checked approximately with Google Earth (Google 2007), as this provides relatively good terrain resolution and can usefully import grid references for all Met Office weather stations to aid the selection procedure. The final selection criterion was dataset completeness. A program was written and executed in MATLAB to extract and manipulate data from the files provided by the BADC, and data were subsequently filtered to remove any hourly data-points tagged by the Met Office as erroneous. Most of the years in the selection had missing entries, and a minimum requirement of 8000 hours of data per year (~90% of the year) was set for the

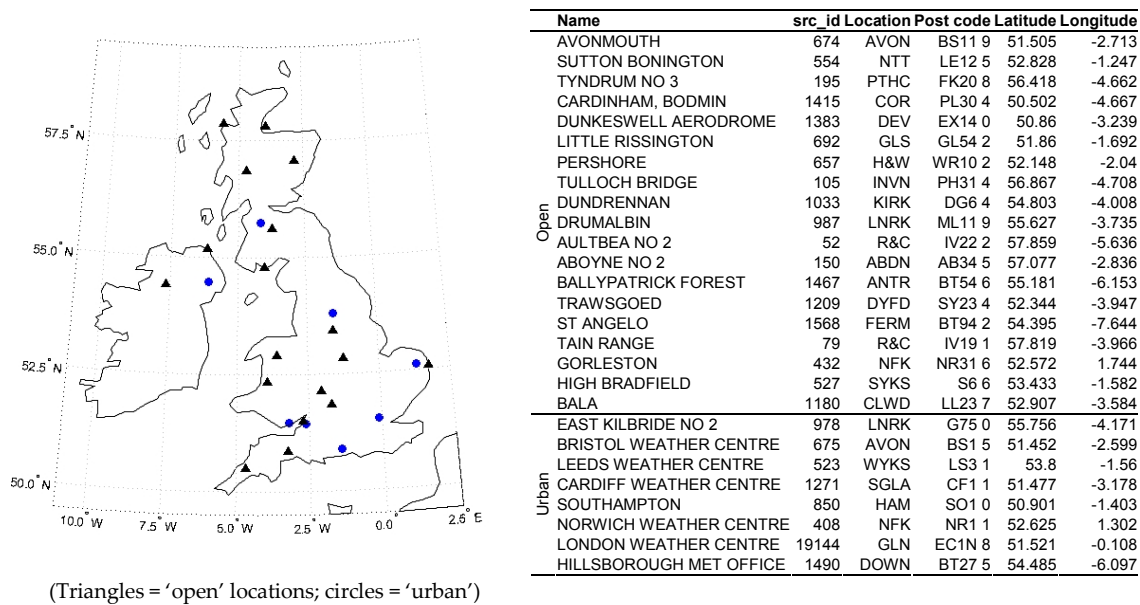
year's wind speed data to be included in the final dataset. A sample of the data is shown in Figure 5-9.



**Figure 5-9: Hourly-averaged wind speeds: data sample**

Two terrain types were represented in the selected dataset: 'open' and 'urban'. Eighteen of the sites, represented by 185 combined years and 1.59 million hours of data, were well-exposed, mostly rural terrain and thus categorised 'open'. In these cases the Met Office's stated standard anemometer exposure is 'over level, open terrain at a height of 10m above the ground' (Met Office 2002), and hence the measured wind resource represents that seen by a turbine mounted on a 10m mast, away from a rural household and without local obstacles. Fewer data were available for 'urban' locations, and eight urban sites were selected represented by 76 combined years and 0.66 million hours of wind-speed data. In these cases the Met Office anemometers were usually mounted upon buildings – typically commercial flat-topped buildings according to the location checks with Google Earth. Unfortunately little information could be gathered about exact anemometer positions, but it was considered reasonable to assume that the Met Office would mount an anemometer in a such manner that it represents, as much as possible, the wind in the local area, and is therefore relatively free from obstructions and a relatively reasonable mounting position for a micro-wind turbine. The locations of the weather stations are shown in Figure 5-10, where urban and open sites are differentiated on the map and in the legend, the latter giving exact grid references. In all cases it was assumed that the turbine would be installed at the anemometer position, and hence no height adjustment of the observed wind speed data was necessary.





(Triangles = 'open' locations; circles = 'urban')

**Figure 5-10: Met Office weather station map and legend**

#### 5.4.4.3 Power curve

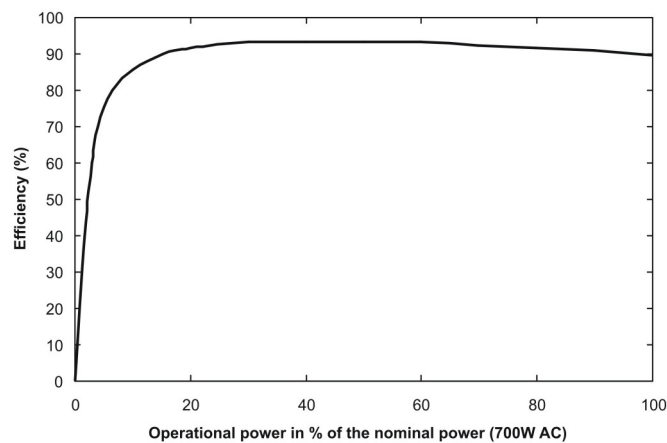
The manufacturer's published power curve was used to estimate power outputs and thus annual electricity outputs. While the reliability concerns outlined in Section 5.3.2 (p.96) were acknowledged, it was necessary to use the curve for the purposes of initial estimations due the lack of further data. The British Standard for determination of turbine power curves states that turbine output power for small wind turbines 'shall be measured at the connection to the load', and that power curves should incorporate all positive and negative instantaneous power peaks, i.e. including any parasitic losses (BSI 2006c p.15 & 74). It was assumed that the power curve was produced in accordance with these requirements, and therefore that it incorporates all losses up to the point of inversion to the household electricity supply. Further work could iterate the output estimations once a power curve produced in accordance with the recent British Wind Energy Association's 'Small wind performance and safety standard' (BWEA 2008b) has been produced.

#### 5.4.4.4 Inverter

In the assumed 'on-grid' format, the micro-wind turbine is connected to the electricity network via an inverter, as outlined in Figure 5-8. This is a prevalent form of installation for residential micro-wind turbines if an electricity network is present, because it negates the need for storage and allows power import to, or export from, the household when required.

The efficiency of a pulse width modulation inverter (such as that installed with the turbine considered here) is affected by switching losses, the internal power consumption of other onboard electronics, and conduction losses (A.M. Massoud, University of Strathclyde, personal communication, 2007). The switching frequency of the semiconductor devices within the inverter is determined by the manufacturer during design, and is therefore constant during operation. The inverter considered here is an adaptation of an inverter

produced for solar photovoltaic systems (SMA 2004) and consumes approximately 4W during operation, and 0.1W in standby. Conduction losses are affected by both modulation index (wind turbine power output) and loading power factor (the household load or grid). For low current applications such as grid-tied micro-wind turbines (micro-generators are limited to 16A by G83/1), the influence of the loading power factor on conduction losses is small, and was therefore assumed constant during modelling (Massoud et al. 2003; A.M. Massoud, University of Strathclyde, personal communication, 2007). It was assumed here that the only variable affecting the conduction losses is the wind turbine power output, which determines the operational power and hence efficiency of the inverter. The efficiency of the inverter varies with operational power as indicated in Figure 5-11 (SMA 2004).



**Figure 5-11: Inverter performance characteristics**

(Source: extracted from manufacturer's datasheet; SMA 2004)

At wind speeds below the cut-in speed of the turbine (~2 m/s), the micro-wind turbine will not operate and hence the inverter will be in standby mode, consuming 0.1W. The turbine will generate power above the cut-in speed and, if the rectifier output of DC voltage is above the inverter's requirements for onboard electronics, the inverter will operate, consuming 4W as indicated above. For a given power input to the inverter ('operational power'), its conversion efficiency was calculated by reference to Figure 5-11. Inverters are required to shutdown in the event of high/low grid AC-voltage, high/low grid frequency, grid failure, or inverter malfunction. Shutdown events were not directly modelled in the estimation procedure, although an 'availability' factor of 90% was included to allow for general shutdown periods of maintenance or breakdown.

The dynamic response of the micro-wind turbine and inverter, as a system, will be of a higher frequency than the 1/3600 Hz (hourly) data used within this study. The characteristics of the inverter in terms of its start-up and shut-down procedures in response to changing wind speeds (and corresponding power production by the micro-wind turbine) could be critical to electricity outputs. Particularly in areas of low wind speeds (where the power input to the inverter could be frequently oscillating around the critical start-up/shut-down condition), the feasibility of grid-tying micro-wind turbines may be

significantly affected by the interaction between the turbine and the inverter, and further research is required in this area.

#### 5.4.4.5 Turbulence

Turbulence is caused by roughness elements, such as trees or buildings, and was assumed here to reduce the output of the micro-wind turbine. The instantaneous wind speed for a steady flow, in the direction of the free-stream (x-direction), can be described as a time-mean wind speed,  $\bar{u}$ , plus a fluctuating wind component  $u'$ :

$$u = \bar{u} + u' \quad (5-3)$$

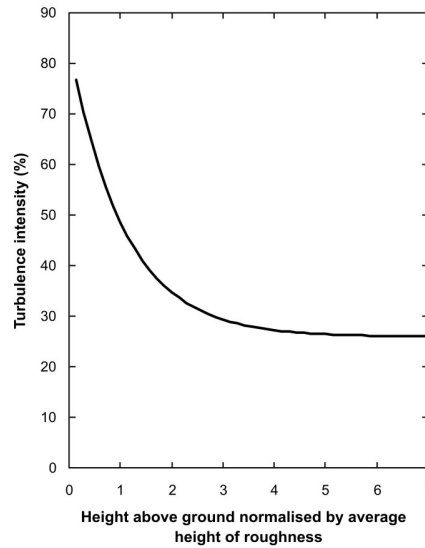
The root mean square of  $u'$  provides a measure of the amplitude (or intensity) of the fluctuations, and is denoted as  $\hat{u}$ . Instantaneous wind speeds in the perpendicular y and z directions can similarly be defined as  $v$  and  $w$ , with equivalent time-mean and fluctuating components. The relative turbulence intensity in direction of the predominant flow is then commonly defined as:

$$I = \frac{\hat{u}}{\bar{u}} \times 100 \quad (5-4)$$

Healey (1983; in Sheinman and Rosen 1992) found that the excess kinetic energy associated with turbulent fluctuations may be significant in comparison with the energy estimated as an hourly mean, depending on the turbulence characteristics of the site and the turbine response time. However, the ability of a turbine to extract any of this extra energy is an area of relatively little empirical knowledge with respect to micro-wind turbines. Horizontal-axis wind turbines (HAWTs), such as that considered here, need to yaw (rotate about their vertical axis) in order to face the oncoming wind so that they can extract energy. Higher levels of turbulence typically lead to more frequent changes in wind direction and speed, and hence may decrease the energy capture of a HAWT. Indeed, a method currently adopted by some practitioners within industry suggests that turbulence will decrease the power output of a HAWT. They incorporate the turbulence intensity as a heuristic safety factor, reducing the output estimation by its percentage value. This approach was taken in this study. Bergey Windpower (2004), for example, recommend a turbulence intensity factor (and hence reduction in output prediction) of 15% for most site-assessment situations, and this value was applied for the 'open' turbine locations.

Turbulence within urban environments is particularly complex due to the complex nature of their layout and roughness elements. Roth (2000) reviewed 14 studies concerning turbulence in the urban environment, and provides an empirical relationship between turbulence intensity and height above ground within an urban environment, for each perpendicular component of the flow. Figure 5-12 shows this empirical relationship for the direction of the free-stream (normalised by the height of the average building), and highlights that the mounting-height of a turbine within an urban environment has a significant affect upon the longitudinal turbulence intensity. It was assumed in this study

that the 'urban' turbines were mounted at approximately the average-roof level, and Figure 5-12 suggests that this corresponds to a turbulence intensity, and hence reduction in output, of approximately 50%.



**Figure 5-12: Turbulence intensity as a function of height in urban environments, in the direction of the free-stream**  
(Adapted from Roth 2000)

Turbulent wind flows, as highlighted above, occur at higher frequencies than hourly mean wind speeds. Thus the present methodology, whilst used within industry, is an approximation that requires validation for micro-wind scale application. It is arguably conservative as it assumes turbulence simply reduces power output with no allowance for any possible increase.

#### 5.4.4.6 Maintenance

To allow for periods of maintenance or breakdown, an availability factor was applied that assumed the micro-wind turbine operated for 90% of the time. It was assumed that all the energy produced by the turbine was either consumed within the household or exported to the grid. If exported, it was assumed that the electricity was consumed locally, and hence transmission/distribution losses were considered negligible (during calculation of the upstream energy-resource displaced by the micro-wind turbine).

#### 5.4.4.7 Air density

Equation 5-1 (p.96) indicated that the power output of a wind turbine is directly proportional to the air density. The ISO Atmosphere model (ISO 1997) was applied to calculate air densities for the altitudes of the weather stations (min: 4m, mean: 110m, max: 395m), and the micro-wind turbine energy output estimations adjusted accordingly. The greatest reduction in air density (and corresponding energy output) due to altitude was 4% from the standard 1.225kg/m<sup>3</sup>.

#### 5.4.4.8 *Summary of methodology*

A dataset of hourly mean wind speeds was used to estimate the electricity output of a commercially-available micro-HAWT. A program was written and executed in 'MATLAB' (The MathWorks 2007) to extract and manipulate wind speed data from a repository provided by the British Atmospheric Data Centre (Met Office 2006a). These data had been recorded at Met Office weather stations around the UK, and twenty-six of these stations were selected to give data during the period 1990–2006. Data were filtered within the extraction program to remove any data-points marked by the Met Office as erroneous. Weather stations were selected on the basis of dataset length (the more years the better), dataset completeness (at least 90% of the year had to have been recorded and to have passed the filtering process), geographical location (to give coverage across the UK), and terrain type ('open' and 'urban'). Eighteen of the sites, represented by 185 combined years and 1.59 million hours of data, were well-exposed, mostly rural terrain and thus categorised 'open', while eight of the sites were 'urban' and were represented by 76 combined years and 0.66 million hours of wind-speed data.

For each location, and for each year's worth of data, the annual electricity output of the turbine was estimated. A second program was written and executed in MATLAB (The MathWorks 2007) to achieve this. The algorithm involved the computer loading each year's worth of data and carrying out the following operations for each hourly mean wind speed:

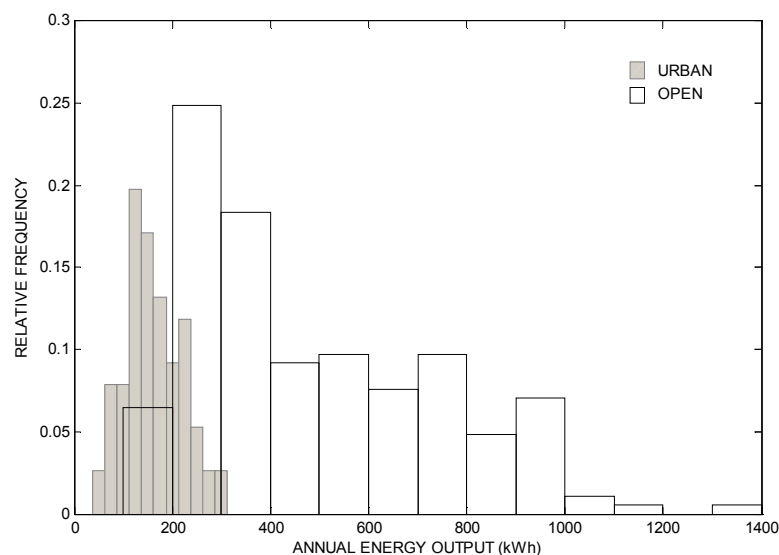
1. The wind speed was entered into the power curve (a stored set of discrete data points, similar to that shown in Figure 5-6), which was linearly interpolated (using the 'interp1' function in MATLAB) to give the power output for that wind speed.
2. If the gross power output was above the threshold requirement for the inverter (4W for onboard electronics), the inverter was considered 'on' and hence consuming 4W. In this case the gross power output was entered into the inverter efficiency curve (a stored set of discrete data points, represented graphically as a continuous curve in Figure 5-11), which was linearly interpolated (using the 'interp1' function in MATLAB) to give the inverter power output. When the gross power output was below the threshold requirement of the inverter, it was considered 'off' and consuming 0.1W in its standby mode for that hour.
3. When operating, the inverter's power output was integrated over the hour to give an energy output, and then multiplied by one minus the turbulence intensity value for the location (the latter being 15% for 'open' sites and 50% for 'urban' sites), and by the availability value (90%). It was also reduced by the density correction factor for the site in question on the basis of station altitude (the largest value of which was 4%).
4. Finally, the annual values were summed to give an annual energy output, which was then normalised to a year of 8760 hours. Each resulting annual energy output is included in the histogram of results in Figure 5-13 of the following section.

### 5.4.5 Results

The following section begins with a presentation of electricity output estimations for the micro-wind turbine. Section 5.4.5.2 then puts these estimations into context by comparing them with representative household electricity demands. The energy-resource and carbon savings enabled by the micro-wind turbine are estimated in Section 5.4.5.3, and finally the embodied energy and carbon are used to calculate the net energy and carbon performance of the turbine in Section 0. In all cases, results are presented briefly with only short, specific discussion. They are then placed in wider context within the overall thesis discussion of Chapter 7.

#### 5.4.5.1 Estimated annual electricity output

The estimated annual electricity outputs of the micro-wind turbine are presented as histograms in Figure 5-13 for both the ‘open’ and ‘urban’ environments. These results revise those previously published by Allen et al. (2008a and 2008b). It was found that a minority of the annual datasets (extracted from Met Office records) had excess hourly datapoints, and these led to an inflation of the original estimated outputs. The inconsistent annual datasets were thus removed during the revised analysis. The estimates shown in Figure 5-13 cover twenty-six geographical sites during the period 1990–2006, of which eighteen were ‘open’ environments (well exposed, mostly rural terrain) while eight were ‘urban’. The sample size of annual energy outputs for open terrains was 185 data points (eighteen locations each with approximately ten years’ worth of estimates) while for urban terrains it was 76 data points (eight locations each with approximately ten years’ worth of estimates).



**Figure 5-13: Histogram of annual energy outputs of the micro-wind turbine for the selection of ‘urban’ and ‘open’ terrains**

The open turbines were estimated to provide considerably more electricity than the urban turbines, with a mean annual output of 486 kWh/yr compared with 161 kWh/yr. The open estimates have a greater variability and a larger range than the urban estimates. The

standard deviation (Table 5-1) provides a measure of variability with respect to the mean, and was 253 kWh the open turbines and 59 kWh for the urban turbines. Both histograms are asymmetric around the mean, with a positive skew. This means that the mean values will differ from the median and modal values. The median of the open sample is 419 kWh/yr (Table 5-1), while a coarse modal range can be taken by inspection of Figure 5-13 as 200–400 kWh/yr. (The modal range is somewhat arbitrary since it depends upon the bin width selected for the histogram.) Similarly, the median of the urban sample is 153 kWh/yr (close to the mean since the distribution is nearly symmetrical) while a coarse modal range is approximately 90–140 kWh/yr (the two outstanding bars of highest frequency).

**Table 5-1: Descriptive statistics for micro-wind energy output estimations**

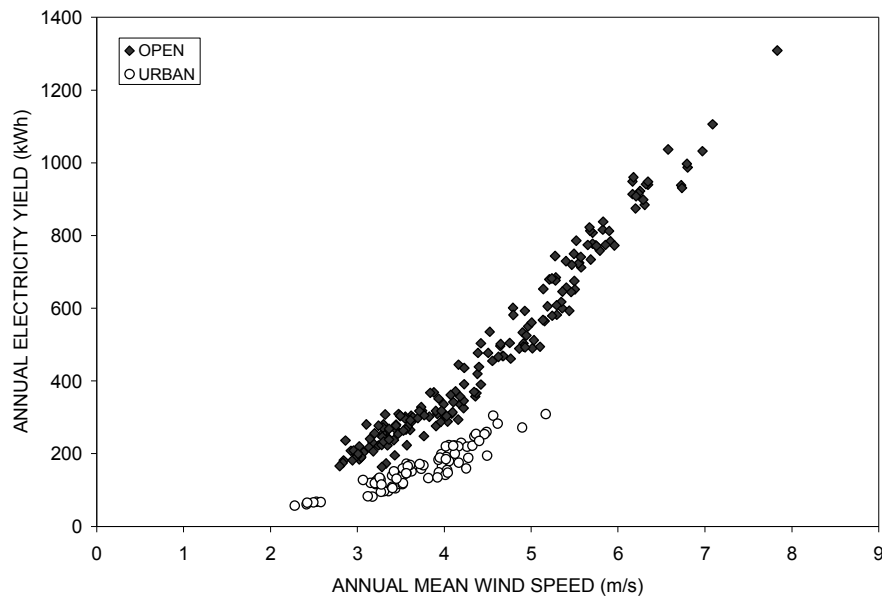
	'Open'	'Urban'	Units
Sample size	185	76	yr
Modal range	200–400	90–140	kWh/yr
Mean	486	161	kWh/yr
Standard Deviation	253	59	kWh/yr
Minimum	163	57	kWh/yr
5 <sup>th</sup> percentile	194	67	kWh/yr
50 <sup>th</sup> percentile (median)	419	153	kWh/yr
95 <sup>th</sup> percentile	940	263	kWh/yr
Maximum	1310	309	kWh/yr

The maximum and minimum values for each sample (Table 5-1) do not necessarily give a representative description of the estimates. It may be that extreme outliers exist, which can misrepresent the sample if viewed in isolation. Describing the data in terms of percentiles is one method of dealing with this issue. The 100<sup>th</sup> percentile may be defined as the data value such that approximately 100% of the sample are at or below this value (Montgomery et al. 2007). For example, the 95<sup>th</sup> percentile is the data value at or below which 95% of the sample reside. The 95<sup>th</sup> percentile of the open estimates is 940 kWh, which is significantly below the outlying maximum of 1310 kWh, and so in this case an outlier does indeed misrepresent the main body of the data sample. The choice of percentiles with which to describe a data sample is arbitrary. In order to describe a large range of the sample, while also ignoring outliers, the 5<sup>th</sup> and 95<sup>th</sup> percentiles were selected to represent the open and urban samples (Table 5-1). 90% of the estimates fall within their respective values, while the outlying highest and lowest 5% are ignored.

The capacity factor is an indicator that compares the actual energy output with that achieved if the turbine were to output its rated power continually. If operating at rated power continually, the annual output of the micro-wind turbine considered here would be 5,256 kWh (a rated output of 600 W for 8760 hours). Capacity factors for the 5<sup>th</sup> percentile, mean and 95<sup>th</sup> percentile of the 'open' annual output estimates are therefore 4%, 9% and 18% respectively, while the modal capacity factor is 4–8%. For the equivalent 'urban' outputs they are 1%, 3%, 5% and 2–3% respectively. These values can be compared with the UK average annual capacity factor of 28% for large onshore wind turbines, ranging from 24% in Durham to 33% in Caithness, Orkney and Shetland (Oswald et al. 2006 in Peacock et al. 2008). It should be noted that large wind turbines are installed in generally-optimal locations in terms of wind resource (Figure 5-3), whereas the locations used during

the present analysis represent a broad geographical spread of micro-wind turbines across the UK.

Figure 5-14 shows the annual electricity output of the turbine for each year's annual mean wind speed for all locations in the dataset, aggregated by the type of terrain ('open' or 'urban'). It indicates that the electricity output of the turbine is correlated with the annual mean wind speed at the location in question. The range of annual mean wind speeds is greater in the case of the 'open' locations, with the majority of the sample falling in the range 3–7 m/s compared to the general range of 3–4.5 m/s for the 'urban' locations. The scatter exhibited in Figure 5-14 is likely to be due to variation in the distribution of hourly wind speeds around each annual mean. Further investigation was outside the scope of the current study, but future work could be to look in more detail at the relationship between annual mean wind speed and annual electricity output.



**Figure 5-14: Annual electricity outputs as a function of annual mean wind speed, for the micro-wind turbine in 'open' and 'urban' terrains**

The wind resource available in urban environments is typically more turbulent than that in open (i.e. rural) environments, and the estimation methodology assumed that this turbulence would reduce the electricity output of the turbine. A measure of turbulence – the turbulent intensity – was used as a heuristic safety factor, reducing electricity outputs by its percentage value. It was 15% for open environments and 50% for urban environments, and it is worth considering the sensitivity of the results to a variation in this assumption. As an extreme, consider that the urban value of 50% grossly over-estimated the power-robbing effect of turbulence and it should instead have been 15% as in the case of the open turbines. This would increase the 5<sup>th</sup> percentile, mean, and 95<sup>th</sup> percentile electricity output estimations to 100 kWh/yr, 241 kWh/yr, and 394 kWh/yr respectively (capacity factors of 2%, 5%, and 8%). The values are still notably smaller than the equivalent open values, reflecting the generally poorer wind resource of the urban locations.



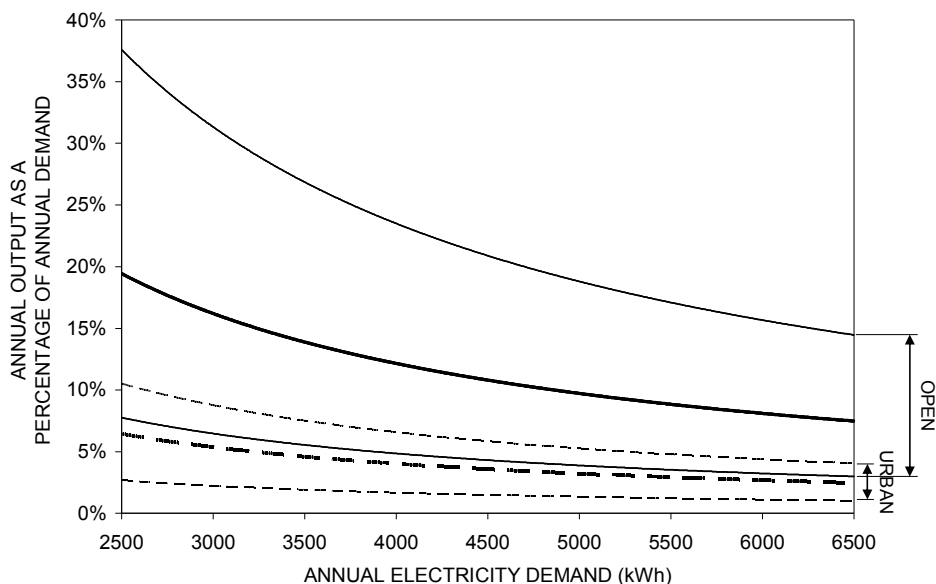
At the time of writing very little empirical data for micro-wind turbines was available with which to validate the modelling results reported above. One small field trial (Encraft 2009) had just published its final report, however, and so a short comparison between the field trial results and the output estimations above is possible. The field trial focused upon urban, building-mounted micro-wind turbines and included only 26 turbines from five different manufacturers (the turbine from one of these manufacturers was that considered here), and so the dataset is very small. Furthermore, the relevant reported results do not distinguish the performance of the turbine considered here from the performance of the four other micro-wind turbines. They are, nevertheless, the best available empirical data for urban micro-wind turbines, and so a short discussion is warranted.

Encraft (2009) found that the mean urban turbine generated 78 kWh/yr – a capacity factor of 0.9% – including downtime when turbines were switched off for maintenance or because of failures. Excluding such downtime, the mean annual output increases to 230 kWh/yr; a capacity factor of 4.2%. The range of the ‘excluding downtime’ sample was reported and was very large; 15 kWh/yr to 869 kWh/yr (the latter apparently being mounted upon a tall, relatively isolated, flat-topped building). These values can be compared to those given in Figure 5-13 and Table 5-1, the latter of which showed that the mean urban turbine was estimated to produce 161 kWh/yr (including an estimated 10% downtime). Given the crude nature of both datasets (the field trial and the estimates), the estimation appears reasonable; although it appears that urban micro-wind can perform better than the estimates of Figure 5-13 when situated on tall isolated buildings.

Encraft (2009) separated four of the micro-wind turbines during their report (from four different manufacturers) and compared their measured electricity outputs with three different estimations: one based upon the NOABL database (BERR 2006) of annual measured wind speeds; one based on a scaled NOABL wind speed; and one based upon measured wind speeds. The latter comparison is of interest here, since that was the approach taken for the estimations presented above. For the four sites given, the turbines produced 41–71% less than the estimations based on measured wind speeds, excluding downtime. In the estimation methodology underlying the results presented earlier in Figure 5-13 and Table 5-1, urban turbines were estimated to suffer a 50% reduction in output due to turbulence, which is a little below the middle of Encraft’s range. (The turbines were further estimated to suffer a 10% reduction due to maintenance etc., but that is not comparable here.) Again, remembering the crude nature of the data, this gives an early indication that the methodology employed here produced reasonable output estimations, although this is far from conclusive.

#### 5.4.5.2 Annual output as a proportion of annual household electricity use

To place the annual output estimates in context it is useful to compare them with the quantity of electricity used by UK households. This is done in Figure 5-15, which shows the annual electricity output of the turbine as a percentage of varying annual electricity demands. The open turbine is represented by solid lines, while the urban turbine is represented by dashed lines. The 5<sup>th</sup> percentile ( $P_5$ ) and 95<sup>th</sup> percentile ( $P_{95}$ ) electricity outputs are the range, while the mean output is shown in bold within this range. Selecting, for discussion, representative output values and representative household demand values from among those shown on Figure 5-15 is non-trivial, since both are stochastic rather than deterministic. The distribution of electricity outputs has a positive skew in both the open and urban turbine's data samples (Figure 5-13), as does the distribution of electricity demands (Section 4.5.4, p.75). In both cases, positive skew indicates that the arithmetic mean demand will reside above the majority of the sample and hence the median and modal averages.



**Figure 5-15: Annual micro-wind output as a percentage of annual household electricity use**

The mean open turbine output was 486 kWh/yr (Table 5-1). This is equivalent to 11% of the mean UK household electricity use of 4500 kWh/yr during the period 1996–2006. While annual mean usage was shown in Section 4.5.4 to vary regionally, such variation is not considered here since turbine outputs were taken from across the whole of the UK rather than being presented regionally. The type of tariff used within a household has a significant influence on mean annual usage: in 2006 it was 4000 kWh/yr for households with standard electricity tariffs compared to 6200 kWh/yr for households with Economy Seven tariffs (Section 4.5.4). Thus, assuming that the turbine is used by a household with a standard electricity tariff, the output of the mean open turbine is equivalent to approximately 12% of average annual usage. This percentage changes to 8% for households on Economy Seven tariffs. In contrast, the mean urban turbine output was 161

kWh/yr, which is 4% of a standard-tariff household, 3% of an Economy-Seven household, and 4% of the overall mean UK household.

Section 4.5.4 indicated that the distribution of annual household electricity usage is both broad and positively skewed, and hence the mean value is above that of the majority of households. A modal range of 3000–4000 kWh/yr was selected, on the basis of BRE (2005a), to represent this skew, although it was noted that an alternative data sample (Hawkes and Leach 2008) indicated that it could be below this range. The median was also recognised as another alternative average but was not selected due to lack of data. To compare with the modal range of electricity demands, the modal range of open and urban turbine outputs can be used, which were approximately 200–400 kWh/yr and 90–140 kWh/yr respectively. Thus, the modal open turbine is estimated to output the equivalent of approximately 5–13% of modal annual electricity usage. The modal urban turbine, in comparison, is estimated to output the equivalent of 2–5%.

From the preceding discussion it is concluded that the average (mean or modal) open micro-wind turbine outputs the equivalent of 5–13% of an average (mean or modal) household's electricity demand each year, compared to 2–5% for urban wind turbines. While these may be taken as 'typical' values, Figure 5-15 gives a wider range of percentages on the basis of 5<sup>th</sup> percentile ( $P_5$ ) and 95<sup>th</sup> percentile ( $P_{95}$ ) electricity outputs. The 5<sup>th</sup> and 95<sup>th</sup> percentile outputs of the open turbine are equivalent to 3–31% of average demands, while the 5<sup>th</sup> and 95<sup>th</sup> percentile urban outputs are equivalent to 1–9% of average demands.

Of course, the percentage values shown on Figure 5-15 do not necessarily represent the proportion of the household's demand that is actually met by the turbine, since it is likely that some electricity will be exported in times of surplus power output. Peacock et al. (2008) estimated that 33–55% of the electricity generated by micro-wind turbines of a variety of sizes would be exported, depending on the dwelling's electricity demand. They calculated these values on the basis of output estimates of four commercially-available micro-wind turbines in the 0.4–2.5 kW range, using two 'suburban' wind speed datasets from Heriot-Watt University's campus both with temporal resolutions of 10 min. The resulting energy output estimations were compared with the electrical demands of 9 dwellings with a temporal precision of 1 min. For comparison with Peacock et al., the British Electrotechnical and Allied Manufacturers' Association (BEAMA 2007) logged, via import/export metering, 6 small wind turbines with an average rated capacity of 14.6kW and an average capacity factor of 9%, and they were found to export 49% of the electricity they generated during June 2006 to May 2007. The relatively large rated capacities of these turbines perhaps make the export rate less relevant to the 0.6kW turbine considered here, but nevertheless the figure is within that Peacock et al.'s modelling-based estimates for smaller turbines.

#### 5.4.5.3 Energy-resource and carbon savings provided by the micro-wind turbine

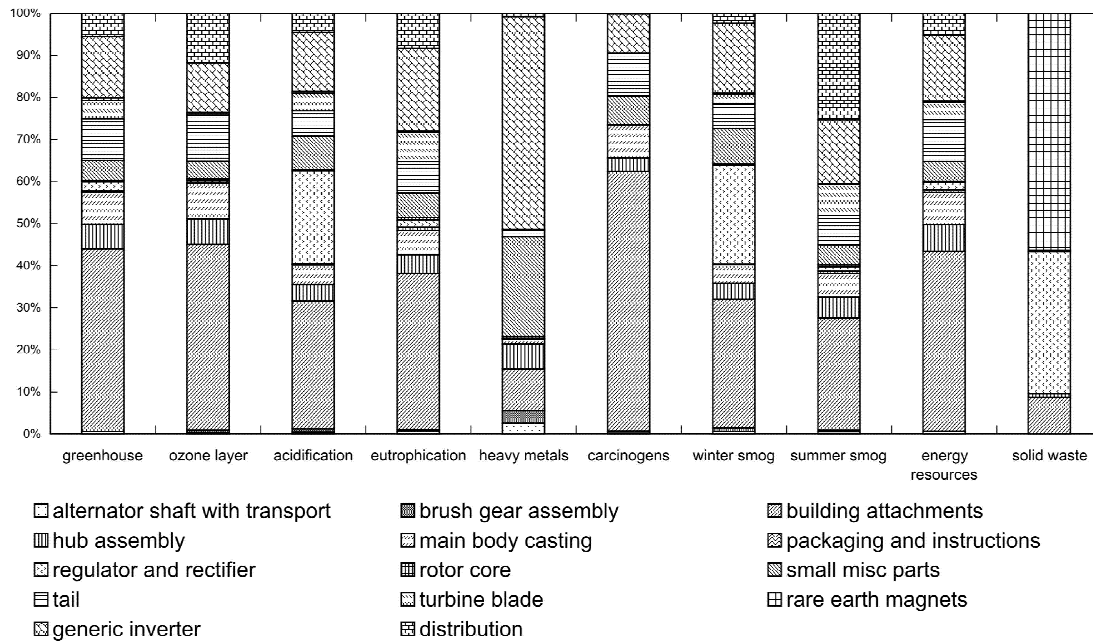
The electricity provided by the micro-wind turbine reduces the use of the established grid, and thus displaces upstream energy-resource use and carbon dioxide emissions. During earlier research underlying this chapter (Allen et al. 2008a and 2008b), the micro-wind turbine was assumed to displace the ‘average’ UK electricity grid of 2005. Section 3.4.6 outlined, however, that this is inappropriate since only marginal generation plant will in fact be displaced, not the average of the grid as a whole. For energy-resource use, the marginal *Energy requirement for energy* (ERE) was estimated as 2.3–2.9 units of energy-resource per unit of electricity, while the marginal carbon-emission factors were 0.49–0.76 kgCO<sub>2eq</sub>/kWh. These factors can be multiplied by the electricity-output of the micro-wind turbine to estimate its energy-resource and carbon saving, and the results are shown in Table 5-2.

**Table 5-2: Estimates of annual energy-resource and carbon savings provided by the micro-wind turbine**

		Output (kWh/yr)	Energy-resource saving (MJ <sub>NCV</sub> /yr)	Carbon saving (kgCO <sub>2eq</sub> /yr)
URBAN	5 <sup>th</sup> percentile	67	555–699	33–51
	Mean	161	1330–1680	79–122
	95 <sup>th</sup> percentile	263	2180–2750	129–200
OPEN	5 <sup>th</sup> percentile	194	1610–2030	95–147
	Mean	486	4020–5070	238–369
	95 <sup>th</sup> percentile	940	7780–9810	461–714

#### 5.4.5.4 Embodied energy and carbon of the micro-wind turbine

The net energy or carbon performance of the micro-wind turbine may be estimated by comparing the estimated output, or overall energy resource/carbon emissions displacement, with its embodied energy or carbon. The latter were calculated as part of a life-cycle assessment undertaken by McManus and published as part of the study by Allen et al. (2008b), which an early version of the work reported here also contributed towards. The approach taken was ‘cradle to end-of-life’, in that all life-cycle stages up to the point of disposal were estimated (e.g. production, transportation to site, operation, and maintenance during operational lifetime). Disposal was ignored because micro-wind systems are relatively new and little data exists about their disposal. In a follow-up publication by Allen et al. (2008a), which also included appraisals of a solar hot-water panel and a solar photovoltaic array, requirements for maintenance of the micro-wind turbine were ignored for consistency with the solar assessments. This second study thus took a ‘cradle-to-operation’ approach (life-cycle impacts such as maintenance and disposal were ignored). The difference between the two sets of micro-wind results were minimal; the total energy requirement (GER) in the first study was 5320 MJ<sub>NCV</sub> compared to 4930 MJ<sub>NCV</sub> in the second, while GHG emissions were 288 kgCO<sub>2eq</sub> compared to 280 kgCO<sub>2eq</sub>.



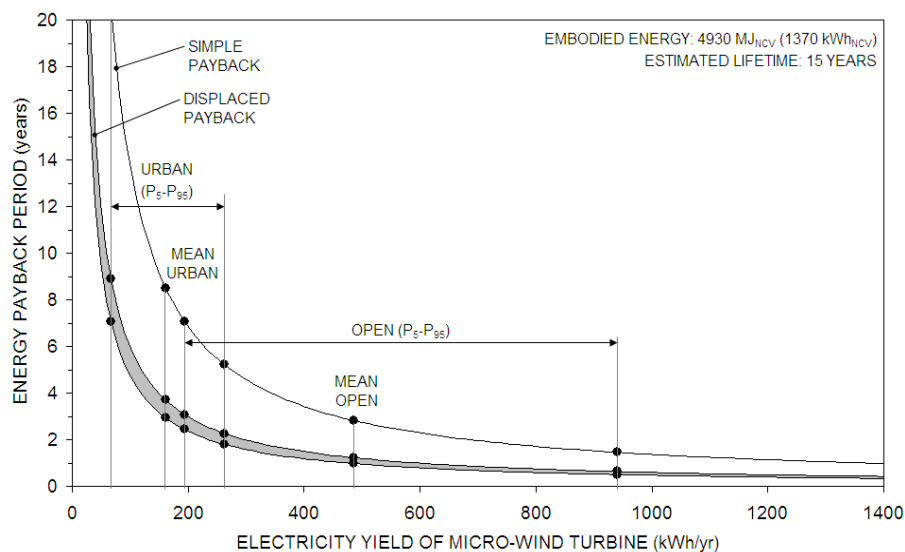
**Figure 5-16: Characterised production data for the micro-wind turbine**

(Source: Allen et al. 2008b, calculated by Dr. M. McManus)

Figure 5-16 shows that the majority of both the gross energy requirement and greenhouse gas emissions are attributable to the building attachment. This is the heaviest part of the turbine, and in the urban building-mounted situations it is made from aluminium while in the open mast-mounted situations it is usually a steel scaffold pole (Allen et al. 2008b). A large scaffold pole for a 10m turbine mounting was calculated to have approximately the same embodied energy as the smaller aluminium building attachment. The next most significant component of the turbine, in energy and carbon terms, is the inverter. Exact inverter components were unknown, although the overall weight of 16 kg was known, along with the fact that the casing is stainless steel. On the basis of component descriptions from electrical engineering colleagues at the University of Bath, it was assumed that the inverter contained a cast iron core and copper or aluminium wire (Allen et al. 2008b). These materials were used to characterise the inverter, and underlie its relatively high embodied energy and carbon. Further discussion of the environmental impacts associated with the production of the micro-wind turbine may be found in Allen et al. (2008b).

#### 5.4.5.5 Net energy and carbon analysis

The energy payback period is the time taken for an energy-supply technology to output enough energy to break even with its energy requirement (Section 2.3.7). When the electricity output of the micro-wind turbine is accounted for simply as the units of electricity delivered by the turbine, as reported in Table 5-1, the *simple energy payback period* (simple EPP) is produced. When the electricity output is accounted for in terms of the total energy-resource displaced, as reported in Table 5-2, the *displaced energy payback period* (displaced EPP) is produced. Both forms of payback period are summarised on Figure 5-17, below. The displaced payback period is shown as a range (the greyed area), since the marginal ERE of grid electricity is uncertain. In both urban and open cases, the 5<sup>th</sup> and 95<sup>th</sup> percentile annual outputs are presented to represent the overall range in each case.



**Figure 5-17: Turbine energy payback period for varying annual outputs**

Figure 5-17 indicates that, when installed in an ‘open’ environment, the micro-wind turbine is estimated to payback its gross energy requirement in 7.1 years or less in ‘simple’ terms. In terms of the energy-resource use it displaces from the established grid, the ‘open’ turbine pays back within 3.1 years. In the mean case, the simple and displaced payback periods are 2.8 and 1.0–1.2 years, respectively. In contrast to the open turbine, the simple payback period of the urban turbine is longer than the turbine’s lifetime given the lowest (5<sup>th</sup> percentile) estimated output. In terms of the energy-resource use it displaces, however, it pays back in 7.0–8.9 years given the lowest (5<sup>th</sup> percentile) electricity output. In the mean urban case, the simple and displaced payback periods are 8.5 years and 2.9–3.7 years respectively.

Similar to the displaced energy payback period (displaced EPP), a carbon payback period (CPP) can be defined that compares the turbine’s embodied carbon with the production of the turbine with the emissions of marginal plant that are avoided through use of the turbine. Again, for any given annual output there is a range for the carbon payback period, since the displacement of marginal plant is uncertain. The relationship between carbon payback and energy payback is fixed by the relationship between the

marginal EREs and marginal carbon emissions factors quoted in Section 5.4.5.3, and the relationship between the embodied energy and embodied carbon. Thus, for any given annual output the minimum carbon payback period is 78% of the minimum energy payback period, and the maximum carbon payback period is 96% of the maximum energy payback period. The displaced EPP values given by Figure 5-17 can be converted to CPPs in this manner. The open turbine will thus avoid enough carbon emissions to break even with the emissions emanating during its production within 2.9 years, and in the mean case this period will be 0.8–1.2 years. The urban turbine, in contrast, has a carbon payback period of 8.5 years or less, and in the mean case this is 2.3–3.5 years.

An alternative net energy indicator is the *Energy requirement for energy* (ERE), or in net carbon terms the *carbon-emission factor*, of the micro-wind turbine (Section 2.3.7.3). These indicators consider the expected lifetime of the turbine, and compare its total energy-resource energy requirement (GER) or carbon emissions to its expected lifetime electricity output. For example, the GER of the turbine is estimated as 4930 MJ<sub>LHV</sub>, and in the mean open case it is estimated to output 1750 MJ<sub>e</sub> (486 kWh) per year for 15 years; a total lifetime output of 26200 MJ<sub>e</sub> (7290 kWh). This gives an ERE of 0.19 MJ<sub>resource</sub>/MJ<sub>delivered</sub> (this could equally have the units kWh<sub>resource</sub>/kWh<sub>delivered</sub>), which means that 0.19 units of energy resource (measured in NCV terms) were sequestered for every unit of electricity delivered during the lifetime of the turbine. Similarly, the GHG emissions occurring during production of the turbine are estimated as 280 kgCO<sub>2eq</sub>, which in the mean open case translates to a carbon emissions factor 0.04 kgCO<sub>2eq</sub>/kWh. EREs and carbon emissions factors for 5<sup>th</sup> percentile, mean, and 95<sup>th</sup> percentile urban and open turbines are shown in Table 5-3, below.

**Table 5-3: Estimates of the ERE and carbon emissions factor of electricity from the micro-wind turbine**

		Lifetime output (kWh)	ERE (MJ <sub>resource</sub> /MJ <sub>delivered</sub> )	Carbon-emission factor (kgCO <sub>2eq</sub> /kWh)
URBAN	5 <sup>th</sup> percentile	1010	1.36	0.28
	Mean	2420	0.57	0.12
	95 <sup>th</sup> percentile	3950	0.35	0.07
OPEN	5 <sup>th</sup> percentile	2910	0.47	0.10
	Mean	7290	0.19	0.04
	95 <sup>th</sup> percentile	14100	0.10	0.02

The values in Table 5-3 may be compared to the equivalent values for other types of electricity generation. The micro-wind turbine is assumed here to displace marginal plant on the established grid, which have an estimated marginal ERE of 2.3–2.9 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and marginal carbon emissions factor of 0.49–0.76 kgCO<sub>2eq</sub>/kWh (these ranges include an estimation of future grid changes out to approximately 2020). Thus the mean open turbine, with an ERE of 0.19 requires 12 to 15 times less energy-resource per unit of delivered electricity than marginal plant. Similarly, the mean open turbine emits 12 to 19 times less greenhouse gas over its life-cycle than marginal plant. Although these comparisons give context to the micro-wind turbine values, the comparison is not strictly valid and must be

viewed accordingly. This is because the electrical outputs of micro-wind have much different characteristics than marginal plant. Whereas the latter is responsive and can provide load balancing for the network, the former is an uncontrollable element on the grid in its current format. This issue will be revisited in the overall thesis discussion of Chapter 7.

#### **5.4.6 Insights from exergy analysis**

As Section 2.3.7.6 outlined, the gross energy requirement of the micro-generators (including the micro-wind turbine) will be similar to the gross exergy requirement since the UK's energy system is based largely upon fossil fuels. It has not, therefore, been calculated nor discussed here. Since energy and exergy are also equal for the output, the concept of exergy has not been employed to analyse the output of the turbine either.

### **5.5 SUMMARY**

This chapter has presented estimations of the electricity output of a commercially-available micro-wind turbine in a selection of 'open' and 'urban' locations across the UK. These estimates were placed in context by comparing them with representative household electricity demands, and they were also used to estimate the overall energy-resource and carbon-emission saving enabled through avoiding the use of the established grid. The electricity output and the energy or carbon savings were then compared with the embodied energy or carbon of the turbine to provide a net energy and carbon assessment. All results will be discussed in the context of other findings of this research in Chapter 7.





## CHAPTER 6

# ANALYSES OF TWO SOLAR MICRO-GENERATORS

### 6.1 INTRODUCTION

Approximately  $2.7 \times 10^{24}$  J of solar radiation arrives at the Earth's surface each year, a vast quantity that represents more than seven thousand times the worldwide consumption of fossil fuels and primary electricity of 2005 (Smil 2006). But converting this abundant energy source into the various forms of useful energy desired by humanity remains an enormous technical and economic challenge. While all societies throughout history have depended directly or indirectly upon a continual influx of solar energy, much of the modern world has altered this pattern through the use of other sources such as fossilised stores of solar energy; coals and hydrocarbons. Fossil fuels have a number of qualities (e.g. they have significant energy densities and are easy to store) that, combined with many technological developments since the late 18<sup>th</sup> Century, have led to their current dominance in commercial energy-supply systems worldwide. Nevertheless, as Smil (2006) points out the potential is clear; there is ample solar energy available to meet humanity's energy demands if it can be effectively harnessed.

Solar energy is used both passively and actively, and it underpins the majority of all other forms of energy used by humanity. *Passive* daily 'uses' of solar energy – those involving no mechanical or electrical systems – include food and other biomass production, space heating of buildings, and daytime lighting. Passive solar-energy use is already making a substantial contribution to the UK building stock although not, in general, by design. BERR (2008a) estimated that the unplanned benefit of solar energy for heating and lighting in UK buildings is approximately 522 PJ/yr, a significant quantity equivalent to half the fuel and electricity used for space heating by all UK households in 2006 (BERR 2008e). Some buildings are designed intentionally to enhance solar energy use, but to date these are a minority in the UK.

Two of the most prominent forms of *active* solar energy use – those that use solar collectors with mechanical and/or electrical systems – are solar photovoltaic (PV) electricity generation and solar water heating, and these two technologies are the focus of this chapter. Similar to the previous chapter that covered the assessment of a micro-wind turbine, the objective of this chapter is to analyse the performance of the two technologies in energy and carbon terms for application in the UK.

## 6.2 OVERVIEW OF SOLAR PHOTOVOLTAIC AND HOT-WATER SYSTEMS

### 6.2.1 Solar photovoltaic systems in the UK

Photovoltaic (PV) cells convert solar radiation directly into electrical energy, the amount of which depending on the properties of the cell and the availability and intensity of the sunlight. PV cells consist of a *junction* between two thin layers of dissimilar semi-conducting materials, known respectively as 'p' (positive) type and 'n' (negative) type semiconductors. Electrons accumulate on the negative layer when the cell is exposed to sunlight, and a deficit results on the other – a voltage being created between the two. Connecting a wire between the two faces causes a flow of electrons between the accumulation and the deficit, and a current is produced (Antony et al. 2007). Individual PV cells are connected together to form a module, and modules are then linked and sized to meet a particular load, forming a PV array.

There is an increasing variety of solar PV technologies, and their design and material constitution vary accordingly. Silicon is the dominant semi-conductor material – traditional *mono-crystalline* and *poly-crystalline* silicon PV modules comprised 90% of all PV sales in 2005 (Compaan 2006). In recent years the dominance of silicon-based PV, combined with the rapid expansion of the PV market (growth rates of 30–50% per year), caused a shortage of silicon feedstock and this has somewhat constrained the global PV market (Compaan 2006; Stryi-Hipp 2008; REN21 2008). The shortage has also driven interest in a variety of alternative material and technological options for PV, including *thin-film* technologies (of the order of 0.001 mm thick as opposed to 0.1–0.5 mm for conventional PV) and *dye-sensitised* cells (see, for example, Compaan 2006 for an overview of three thin-film materials and Peter 2007 for discussion of dye-sensitized PV technologies). Both are developing at pace; thin-film technologies in particular. The latter are becoming increasingly commercially viable; annual production grew 123% to 0.89 GW in 2007 (Renewable Energy Focus 2009). A further and relatively recent innovation has been *building-integrated* PV (BIPV); photovoltaic materials that are used to replace conventional building materials in parts of a building envelope such as the roof, skylights or facades.

Installation requirements in the UK for prominent forms of solar PV include an appropriately oriented (SE–SW facing) roof with minimal shading and, ideally, a pitch angle of 35–40 degrees or less (although flat-roof installations are possible), plus sufficient roof strength (Energy Saving Trust 2006a). The size of PV array required by a household depends primarily upon the electricity demand, the type of PV cell used, available roof-space and budget. Typical systems cover 10–15 m<sup>2</sup> of roof area and are rated at around 1.5–2 kW<sub>p</sub> (Energy Saving Trust 2005c).

PV cell efficiency is an oft quoted performance indicator, but it is not necessarily the most suitable when comparing different systems. It is important at the design stage because it influences the area required for a given energy output, and it is also important to obtain a system efficiency that is as close as possible to the efficiency of the PV module chosen. However, to assess the performance of a PV installation the system output (expressed as kWh/kW<sub>p</sub>) and the performance ratio (ratio of the AC electrical output of the

actual system to that of an ideal system) are more useful indicators (DTI 2006b). Nevertheless, an idea of conversion efficiencies is worthwhile. The UK's 'Domestic Photovoltaic Field Trial' found that overall system efficiencies (AC electrical output compared to insolation) were approximately 10.5% for mono-crystalline PV arrays and 4.5% for thin-film building-integrated tiles, for systems without major loss mechanisms (DTI 2006b).

In the prevalent 'grid-connected' format, solar PV systems are connected to the electricity network by an inverter, similar to the case of the micro-wind turbine examined in the previous chapter. Any excess electricity unused by the household is exported to the grid. The *solar fraction* presents the output as a proportion of demand, and does not distinguish between electricity used on site and that exported. A recent UK field trial report analysed the performance of 272 individual PV systems across 17 sites found that the majority of the sample provided solar fractions of between 20 and 80% with a mean of 51% (DTI 2006b). The annual outputs underlying these values ranged from below 400 kWh/kW<sub>p</sub> to more than 900 kWh/kW<sub>p</sub>. All systems with outputs less than 600 kWh/kW<sub>p</sub> had clearly identifiable losses such as long-term inverter outages or high levels of shading, while those below 750 kWh/kW<sub>p</sub> usually exhibited occasional losses due to shading, short-term inverter outages or inverter thresholds (DTI 2006b). The modal range of the sample was 701–800 kWh/kW<sub>p</sub>. Interestingly, the data sample suggested that location was not a prime determinant of performance; output values were dominated by loss mechanisms and the effect of location did not register comparatively in the analysis.

Grid-connected solar PV is the fastest growing energy supply technology in the world, with 50% annual increases in cumulative installed capacity in 2006 and 2007, giving a cumulative total of an estimated 7.7 GW<sub>p</sub> (REN21 2008). This translates to approximately 1.5 million homes with grid-connected rooftop solar PV worldwide. Germany accounted for half the global market in 2006, with an installation that year in the region 0.85–1 GW<sub>p</sub> (10–12 W<sub>p</sub> per capita) making a cumulative total of 2.8–3.1 GW<sub>p</sub>. Other significant installations during 2006 occurred in Japan, Spain, and the U.S.A., with 300 MW<sub>e</sub> (2.4 W<sub>p</sub> per capita), 100 MW<sub>p</sub> (2.2 W<sub>p</sub> per capita), and 100 MW<sub>p</sub> (0.3 W<sub>p</sub> per capita) added respectively. Off-grid solar PV, for comparison, totalled 2.7 GW<sub>p</sub> of installed capacity worldwide in 2006 but with a much lower growth rate.

The UK is lagging behind these leading countries. BERR (2008a) indicates that 3.4 MW<sub>e</sub> or 0.06 W<sub>e</sub> per capita of solar PV capacity was installed between 2005 and 2006; an installation rate of 170–200 times less, per capita, than Germany. By the end of 2006 the total installed capacity of PV in the UK was estimated by BERR (2008a) to be 14.3 MW<sub>p</sub> or 0.3% of total renewable electricity capacity; presented as a just-perceptible black area on Figure 5-2 (p.89). By the end of 2007 there were approximately 3000 solar PV installations of less than 50 kW<sub>p</sub> (hence classified as micro-generation) across the UK, with a total capacity of 10.3 MW<sub>p</sub> and an estimated annual output of 7.2 GWh<sup>10</sup> (Element Energy

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<sup>10</sup> This estimation was on the basis of a performance of 850 kWh/kW<sub>p</sub>.

2008a). 3000 installations represent approximately 0.005% of the housing stock of 2006, and so the potential for increased use of solar PV in the UK is large.

### 6.2.2 Solar hot-water systems in the UK

Solar hot-water (SHW) collectors absorb insolation and transfer heat into water, usually for use within households although also for swimming pool heating and in some industrial or commercial applications. SHW for household application is the focus of this chapter. There are a wide range of SHW collector designs that may generally be categorised into one of two forms: *flat-plate* collectors or *evacuated-tube* collectors. Flat-plate collectors consist of thin absorber sheets backed by a grid or coil of tubing through which a heat-transfer fluid flows, and are situated in an insulated casing glazed with glass or polycarbonate. Cool water enters the collector and receives heat from the absorber material, and thus exits the panel at a higher temperature than at entry. In contrast to flat-plate collectors, evacuated-tube collectors consist of a series of modular, typically glass, tubes. Within each tube resides another, and the space between them is evacuated providing a layer of insulation in a similar manner to double-glazing. Insolation is absorbed within the inner tube, the method depending on the design, and thermal energy is again subsequently transferred into water and is stored ready for use.

Collectors are connected either *indirectly* or *directly* to the hot water storage tank. Indirect SHW systems have a closed circuit of fluid flowing between the collector and the storage tank, and a heat exchanger is used to transfer heat into the hot water to be used by the householder. In contrast some collectors are plumbed directly to the hot water cylinder, and the water flowing through them is that ultimately used by the householder. Low temperatures can cause freezing of the heat-transfer fluid, and conventional methods of dealing with this are either to use antifreeze (within closed-circuit, indirect systems) or to employ a 'drainback' method. The direct SHW system analysed later in this chapter employs an unconventional method of using silicon tubing within its flat plate collector, and hence the expansion of water caused by freezing does not cause a problem. In typical household installations an electrically-powered pump is used to circulate water around the system and through the collector, although *thermosyphon* systems are an alternative that passively circulate water on the basis of temperature differences.

Typical solar collectors convert approximately 35–40% of the insolation arriving at their surface into the thermal energy within the water entering their storage tanks (Energy Saving Trust 2006b; The German Solar Energy Society 2005), although storage and distribution losses later accrue. A field trial of eight SHW systems found overall system efficiencies (insolation to hot water in the tank at the time of run-off) to be 22–34% for six flat-plate systems compared to 39% for two evacuated tube systems, including storage losses but excluding household tank-to-taps distribution losses<sup>11</sup> (DTI 2001b). Collector efficiencies are important at the design stage because they influence the collector area required to meet a specified hot water demand. They are not, however, the only criterion of performance. A slightly less efficient system may simply need a slightly larger area than

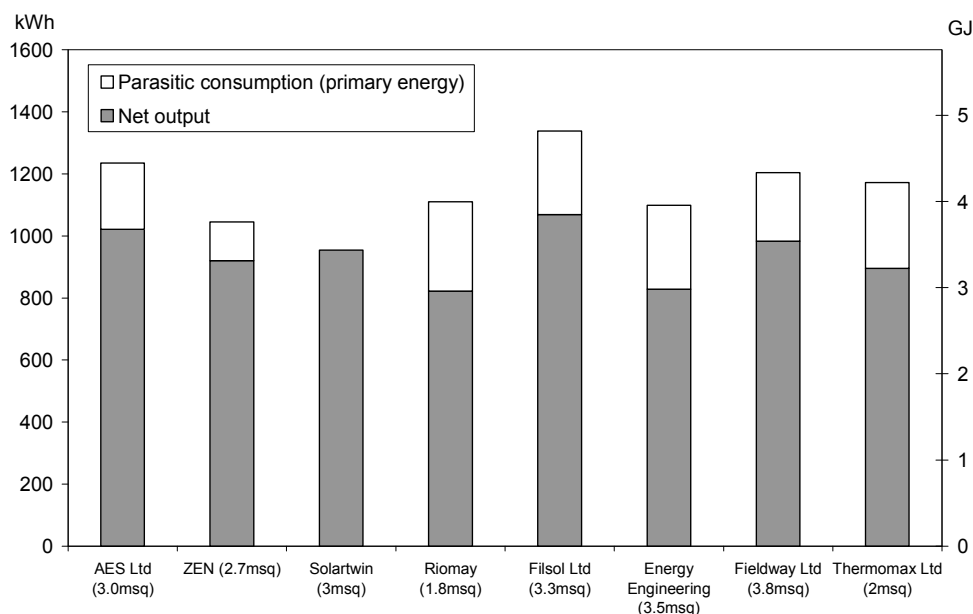
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<sup>11</sup> These efficiency values are based upon the solar insolation arriving on the gross collector area of the SHW systems.

a more efficient system to give the same energy output, which is not necessarily a disadvantage.

The appropriate specification and dimensioning of a solar hot-water system is vital for effective performance. Typical collector areas in the UK are 2–5m<sup>2</sup> (Energy Saving Trust 2006b) and common installation requirements include a south-east to south-west facing roof space with minimal shading for most of the day; appropriate roof strength; and (in some cases) space for an additional water cylinder (Allen et al. 2008c). In temperate climates, such as that in the UK, a usual design objective is that a SHW system for one-family homes should provide a solar fraction (the percentage of demand met with solar hot-water) of about 90% of hot water demand during summer months (The German Solar Energy Society 2005). When a system is properly sized the addition of extra collector area would not necessarily cause a corresponding increase in annual solar fraction. In summer months the system may produce excess and thus wasted heat, which would lead not only to frequent high thermal loads on the collectors (causing stagnation) but also to a lower cost-effectiveness (additional costs are higher than additional output). In periods of lower irradiation, the real output would be higher, but the annual (useful) annual output per m<sup>2</sup> would be lower than a more appropriately-sized system.

DTI (2001b) undertook side-by-side testing of eight commercially-available SHW systems, and used the results to develop an energy-output model for those systems. This relates daily insolation to daily hot water output, and the analysts used this to estimate annual outputs for an assumed installation in Kew, London. The results are shown in Figure 6-1. The total height of each bar represents the estimated hot water output, while the white portion of the bar represents the primary energy used to power the electrical pumps within the hot-water systems. The 'net output' is then the difference between the two.



**Figure 6-1: Estimated annual hot water output for eight solar hot-water systems (with specified absorber areas) in Kew, London, assuming 150 litres/day runoff at 6pm and solar-only storage**  
(Source: DTI 2001b)

Figure 6-1 shows that the mean estimated hot water output (the total height of each bar) is 4.1 GJ<sub>th</sub>/yr (1200 kWh<sub>th</sub>/yr) with a range 3.4–4.8 GJ<sub>th</sub>/yr (950–1300 kWh<sub>th</sub>/yr). These values apply specifically to a daily hot water demand of 150 litre/day drawn off at 6pm, from a separate solar storage cylinder. These figures equate to solar fractions of 33–46% with a mean of 40%. Figure 6-1 also indicates, however, that it is important to consider parasitic electricity consumption in order to assess the net effect of using each system. The Solartwin system, using a small PV array to provide electricity for its pump, does not use grid electricity. It therefore moves from eighth to fourth place when the primary energy required to power the other systems is accounted for.

For comparison, the Energy Saving Trust (EST) has estimated a wider range of 2.9–6.3 GJ<sub>th</sub>/yr (800–1750 kWh/yr) for typical installations (Energy Saving Trust 2006b). Typical demands underlying these outputs were not specified by the EST, but they suggest that typical solar fractions are in the range 40–50%. A variety of UK manufacturers suggest that annual solar fractions of up to 70% are in fact possible (for example, see Solartwin 2006, Radford 2008, Genersys 2007, Simplee Solar 2007, and Smart Energy 2009). The remaining hot water requirement is provided by an auxiliary heating system, usually fuel- or electricity-based.

Solar hot-water systems contribute significantly to hot water supply in China, Israel, Japan, Turkey and several EU countries (although not the UK). China has by far the largest area of installed collectors; 97 million square metres or 0.07 m<sup>2</sup> per capita, representing 65% of the global total and an estimated 68 GW<sub>th</sub> of installed capacity (REN21 2008). The UK, in contrast, had an estimated 0.12 million square metres (Energy Saving Trust 2006b) or 0.002 m<sup>2</sup> per capita in 2006; 35 times less per capita than China. The majority of installations

worldwide are in the form of residential hot water systems, although others include swimming pool heaters and commercial and industrial applications. Worldwide growth in the rooftop solar hot-water industry was 19% in 2006 (REN21 2008).

SHW is currently the largest and most established micro-generation industry in the UK, and there were approximately 100,000 installations at the end of 2007 (Element Energy 2008a) generating an estimated 130–140 GWh<sub>th</sub>/yr. Installation rates are of the order of a few thousand a year; recent data indicated an annual installation rate of 4000 units in 2004 (Energy Saving Trust 2006b). But as indicated with the per capita figures above, total installed numbers are small in national terms – 100,000 installations represented 0.4% of the total UK housing stock in 2006 (Appendix A). Similar to solar PV, the potential for increased use of SHW in the UK is large.

### 6.2.3 Net energy and carbon performance of solar technologies

Like the case of wind turbines, much of the interest in solar energy-supply technologies such as solar PV arrays and SHW systems is driven by the desire to reduce greenhouse gas emissions and provide energy security by reducing use of, and dependence upon, fossil fuels. Short energy and carbon payback times relative to the overall lifetimes of these technologies are required if their net effect is to be positive in these terms.

Since both the solar PV and solar hot-water industries are more established than the micro-wind industry, it is unsurprising that more energy analyses and life cycle assessments of the two solar technologies may be found in the literature. A brief review of some recent published energy payback periods for both technologies is now presented. While these figures are instructive they were not generally produced for the UK, a notable shortcoming since the results of an energy analysis or life cycle assessment are technology, location, and time specific – they depend upon the system's design and material makeup as well as the energy supply system underpinning their production, all changing (albeit relatively slowly) over time and the latter at least varying by country. In addition, as in the case of micro-wind, the location of a solar supply technology affects its ambient energy resource and hence its energy output. This indicates that further research would be beneficial in order to widen the evidence-base for the energy and environmental performance of solar technologies for residential application in the UK.

Bennett (2007) carried out a review of life cycle assessments of a variety of micro-generators on behalf of the UK's Energy Saving Trust. Within this study he reviewed seventeen LCA studies of micro-PV, although again these were studies from other countries and hence not necessarily representative of UK manufacturing and/or operational conditions. He adjusted the published payback times to represent a UK situation; for UK insolation and the UK electricity network that PV would displace (he assumed a marginal plant carbon emissions factor of 0.568 kgCO<sub>2eq</sub>/kWh which is equal to BRE 2005b; Section 3.4.6). He found that the 'most recently reported [energy payback period] values from comprehensive peer-reviewed assessments show close agreement when standardised to UK conditions' and reported a mean value of 5 years as a 'good conservative estimate for systems installed today' (Bennett 2007). These figures represent grid-connected solar PV



displacing the UK grid. Bennett found that thin-film technologies already deliver lower displaced EPPs of 1–1.5 years, being less energy intensive to manufacture, but are generally more expensive. Carbon payback times showed greater variation, but Bennett summarised a ‘reliable range’ of 6–8 years for mono- and poly-crystalline modules compared to 3–6 years for thin-film technologies. Estimated lifetimes (on the basis of typical guarantee periods) were 25 years.

Alsema and colleagues have been active in energy analysis and LCA research of solar PV for a number of years – e.g. Alsema (2000), Wild-Scholten and Alsema (2005) or Alsema et al. (2006). In the most recent of these three studies Alsema et al. (2006) estimated that crystalline silicon PV systems would have displaced energy payback periods of 1.5–2 years for southern-European locations (annual irradiation: 1700 kWh/m<sup>2</sup>) and 2.7–3.5 years for middle-European locations (annual irradiation: 1000 kWh/m<sup>2</sup>, appropriate for the UK). They indicated that there are ‘clear prospects’ for embodied energy reductions that could reduce this to within one year in the near future. Thin-film technologies, for comparison, had payback periods of 1–1.5 years for southern-European locations. Carbon emissions were found to be in the overall range 25–32 gCO<sub>2eq</sub>/kWh with the potential of reducing to 15 gCO<sub>2eq</sub>/kWh in the future. Like the carbon results presented for wind turbines in the previous chapter (Section 5.2), these figures are significantly lower than established fossil-fuel dominated electricity systems around the world. All figures were based on the life cycle inventory that the authors had previously published in Wild-Scholten and Alsema (2005) but with updates in certain areas. They estimated PV lifetimes as 30 years.

Tovey and Turner (2008) recently estimated the net energy performance of monocrystalline and polycrystalline PV arrays specifically for the UK. This work has been published since the research underlying this chapter and associated publication (Allen et al. 2008a) was carried out. They made their electricity output estimations on the basis of monitored PV performance data from two building-integrated crystalline PV installations at the University of East Anglia; data that they subsequently combined with insolation data from a selection of six UK locations in order to estimate realistic outputs for a variety of azimuth and tilt angles. Similar to the research reported in this chapter, they used the life cycle inventory data published by Wild-Scholten and Alsema (2005) to estimate the embodied energy of the PV arrays.

Tovey and Turner presented embodied energy values as kWh<sub>e</sub>/kW<sub>p</sub>; a quantity of energy in *electrical equivalent* terms. Although not stated by the authors, this is an application of the opportunity cost convention as outlined, for example, by Roberts (1980), and effectively produces a *displaced* energy payback period or gain ratio (as defined in Section 2.3.7, p.19). Tovey and Turner converted the embodied energy from primary energy to an electrical energy equivalent, which in the UK is a reduction by a factor of approximately three (the primary energy requirement, or ERE, of a unit of grid electricity is approximately 3; see Section 3.4.5, p.50). An energy payback period calculated in these terms will be three times shorter than one in which the embodied energy is accounted for in primary terms. This is, in effect, the same as the approach taken for *displaced* net energy metrics as defined in this thesis. While in this latter case the embodied energy is presented in primary terms, the

electricity output is multiplied by approximately three (the ERE of electricity) to calculate the primary energy it displaces. The two approaches have differing conceptual approaches but an equal effect. The 'opportunity cost' considers that if the primary energy invested in the PV array was instead invested in the current electricity system, approximately one-third of it would be converted into electricity. The energy investment is therefore reduced by a factor of three to put it into 'electrical-equivalent' terms, and compared with the electricity output of the PV array. In contrast, the 'displacement' approach converts the electricity output of the PV array into an equivalent quantity of primary energy and thus increases it by a factor of three, and compares this with the primary energy invested into it.

Tovey and Turner presented their net energy results as 'gain ratios' rather than payback periods. Gain ratios are the reciprocal of the ERE defined in Section 2.3.7.3. They found that, given a 'typical annual solar irradiation of 1000 kWh/m<sup>2</sup>', a mono-crystalline system would provide 3.2 to 4.6 times as much energy as required during its lifecycle, for assumed operational lifetimes of 20 to 30 years respectively. These figures translate to a displaced energy payback period (EPP) of approximately 6.4 years. In contrast a polycrystalline system would provide a displaced EGR of 2.9 to 4.3 for 20 to 30 year lifetimes respectively, which translates to a displaced EPP of approximately 7 years. The similarity of the results indicate that although the module efficiency of the mono-crystalline system was 3.0–3.5% higher than that of the polycrystalline system, the higher embodied energy requirements of the mono-crystalline system offset the efficiency benefit and hence give similar net energy results.

Bennett (2007) also reviewed eleven LCAs of solar water heating systems published since 1996, although none were for the UK but rather Greece, India, Australia, Cyprus, Brazil, Italy, and Pakistan. Excluding the Brazilian study, which had an unusual installation, the mean energy payback time was reported as 1.4 years and the mean carbon payback time 2 years. These values are *displaced* payback times; the energy output of the SHW systems is valued as the quantity of primary energy displaced from an auxiliary heating system, such as a gas boiler and its upstream gas-supply system (see Section 2.3.7). The systems summarised had expected lifetimes of 15–20 years, and hence they would provide a primary energy and carbon saving for the majority of their operational lifetimes. 70–80% of the energy requirements and carbon emissions were associated with the production of the materials within the SHW systems (as opposed to other life-cycle stages such as transportation of materials, assembly, installation, maintenance, and disposal). Bennett adjusted one of the two Italian LCAs to estimate representative payback times for the UK's solar resource, and included impacts for transportation from Italy. He found that the (displaced) energy payback time would be 2.0–3.8 years while the carbon payback time was 2.4–4.4, and concluded these as representative values for SHW in the UK.

In summary, existing literature suggests that both solar PV arrays and solar hot-water systems perform well in net energy and carbon terms, paying back their embodied energy and carbon well within their lifetimes. However, as discussed both here and in earlier sections of this thesis, the results of a net energy analysis or life cycle assessment are technology, location, and time specific. In the case of both solar PV and solar hot-water the

technologies are diverse and in some cases developing fast (although the majority of commercially-available PV is still conventional mono- or poly-crystalline silicon technology), and there is a notable lack of studies undertaken specifically for the UK; hence Bennett's estimates to adjust studies from other countries. This indicates that further UK-specific research would be beneficial in order to widen the evidence-base for the energy and environmental (e.g. carbon) performance of these solar technologies for residential application in the UK.

In addition to providing net energy and carbon data specific to the UK, the research reported in this chapter also contributes to a wider, and novel, 'integrated appraisal' methodology that includes economic and broader environmental impact assessments. The research reported here also incorporates insights from exergy analysis where appropriate, of which there is a paucity in the literature for solar technologies in the UK.

#### 6.2.4 Summary

There is ample insolation worldwide to meet global energy demand, but it is yet to be effectively utilised and other energy forms – primarily fossil fuels – currently dominate most commercial energy systems.

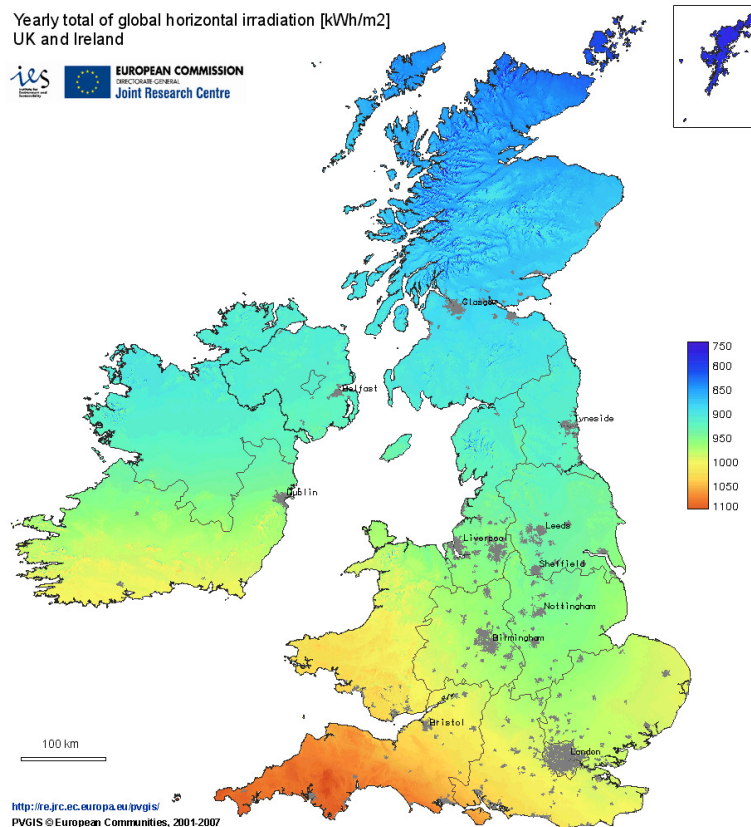
Two prominent *active* solar energy technologies (those involving mechanical and/or electrical systems) for households are solar photovoltaic arrays and solar hot-water systems. Globally, the growth in these solar technologies is significant; approximately 19% per annum for solar hot-water systems and 50% for solar PV in recent years (REN21 2008). But neither technology plays a significant role in the UK, even though they are apparently able to meet a reasonable proportion of household demand on the basis of the UK's solar resource. There is a large potential for increased use.

Much of the interest in solar energy-supply technologies is driven by the desire to reduce carbon emissions and provide energy security by reducing use of, and dependence upon, fossil fuels. Short energy and carbon payback times relative to the overall lifetimes of these technologies are required if their net effect is to be positive in these terms. It appears that both solar PV and SHW perform well in net energy and carbon terms, but UK-specific evidence is lacking. The remainder of this chapter addresses the need for more UK-specific information, with energy and carbon analyses of a solar photovoltaic array and solar hot water system. Since the concept of exergy adds additional information to the solar hot-water system analysis, an exergy analysis of the hot water output is also presented. The remaining sections begin with a short description of the UK's solar resource, before the solar PV and SHW system analyses are presented in turn.

### 6.3 THE SOLAR RESOURCE IN THE UK

Solar irradiance is weakened as it passes through the Earth's atmosphere by absorption and reflection, and partially converted by dispersion into diffuse irradiance. The irradiance on the horizontal is known as the global irradiance, which is the sum of the direct and diffuse components (Eicker 2003).

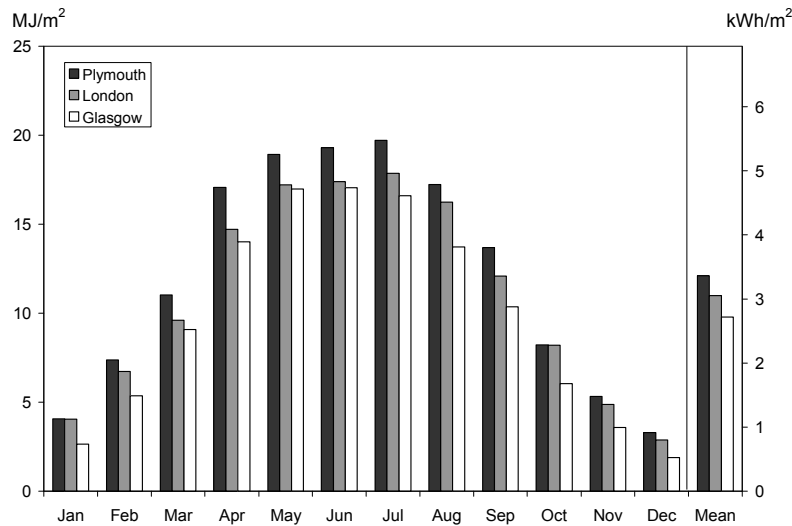
The global irradiation available to a solar collector varies with its azimuth, pitch and geographical location. Figure 6-2 shows the global horizontal irradiation arriving at a horizontal surface for locations across the UK and Ireland. Locations ranging from Glasgow and Aberdeen (Scotland) to Plymouth (South-West England) receive approximately 3200 to 3900 MJ/m<sup>2</sup> (880–1100 kWh/m<sup>2</sup>) of global irradiation annually on a horizontal surface, assuming no shading. For a typical UK roof pitch of 15–50°, and for SE to SW facing installations, the insolation available will be increased by approximately 10–15% from these values (BSI 1989). This range of installation possibilities was assumed in this chapter, and the annual gross solar resource available to a solar collector was thus estimated as 3500–4500 MJ/m<sup>2</sup> (960–1300 kWh/m<sup>2</sup>).



**Figure 6-2: Yearly global horizontal irradiation (kWh/m<sup>2</sup>), UK and Ireland**  
(Reproduced with permission from Suri et al. 2007)

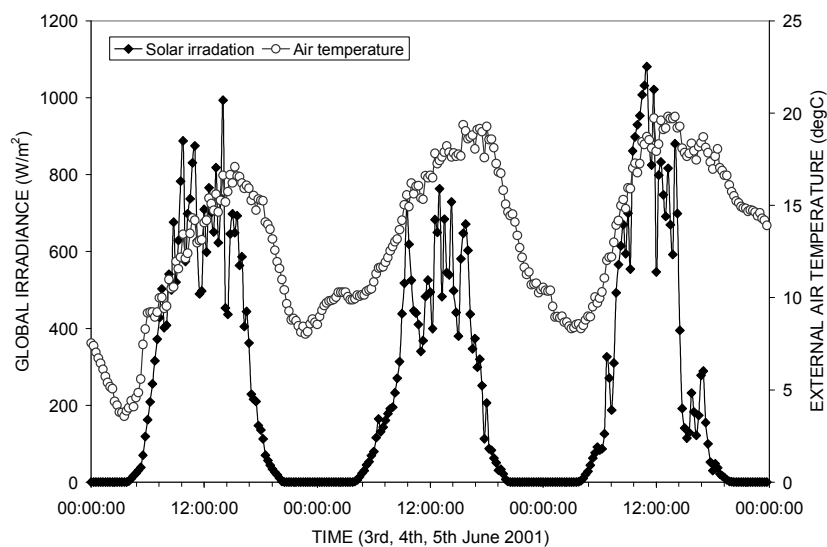
Insolation varies with time of day and season. Figure 6-3 shows that summer days receive a much greater quantity than winter days in the UK. During the winter the sun is lower in the sky and hence, ideally, a solar panel would increase its pitch at such times to capture the maximum possible global irradiation. Optimal inclination angles vary across

the UK and were calculated by Suri et al. (2007). For Plymouth, for example, they ranged from  $67^\circ$  in December to  $13^\circ$  in June. In the majority of residential solar applications, however, tracking equipment is impractical and fixed installation angles are dictated by roof pitch.



**Figure 6-3: Average daily global irradiation during different months of the year, for a solar collector inclined at  $25^\circ$  to the horizontal**  
(Source: Suri et al. 2007)

Figure 6-3 also reiterates the difference between different geographical locations. For an inclination of  $25^\circ$ , Plymouth receives 124% of the irradiation received in Glasgow, and 110% that of London. Figure 6-4 illustrates variation of insolation across a day. The data points are 15-minute averages recorded by the DTI (2001b), and exhibit significant variation across short time periods, probably due to passing clouds affecting the irradiance received by the sensor.



**Figure 6-4: 15-min average solar irradiation, 3–5 June 2001 (southern England)**  
(Source: DTI 2001b)

## 6.4 THERMODYNAMIC ANALYSIS OF A SOLAR PV ARRAY

### 6.4.1 Introduction

The analysis presented here is brief compared to the micro-wind analysis of Chapter 5 and the SHW assessment presented in Section 6.5. This is because the electricity outputs of the dominant and established silicon-based PV systems are relatively well understood and have been the subject of a recent UK field trial which provides practical (rather than laboratory-based) performance data. The following analysis presents estimated electricity outputs of a mono-crystalline PV array and then uses this information to calculate its net energy and carbon performance. Outputs are also put into context through comparison with representative household electricity demands.

### 6.4.2 Background to the research

In contrast to the micro-wind and solar hot-water studies, the integrated appraisal (of which this work forms part) was not conducted through collaboration with a UK manufacturer. Interest from PV manufacturers was not forthcoming in the manner of the micro-wind and solar hot-water manufacturers. In this case the lack of a collaborating manufacturer did not constrain the research, since life-cycle inventory data was available in the literature (Wild-Scholten and Alsema 2005) for the more conventional crystalline silicon technologies that this study set out to analyse. The life cycle assessment (LCA) element of the collaborative 'integrated appraisal' (Section 2.6) used this LCA inventory data to estimate the production impacts of a generic mono-crystalline solar PV array. These impacts included the gross energy requirement and associated carbon emissions that are taken as an input in this chapter. The integrated appraisal as a whole was published by Allen et al. (2008a).

### 6.4.3 The solar PV array

The system considered here is a generic grid-tied, mono-crystalline solar PV system of 15m<sup>2</sup> and 2.1 kW<sub>p</sub>, as outlined in Figure 6-5. The assumed lifetime was 25 years.

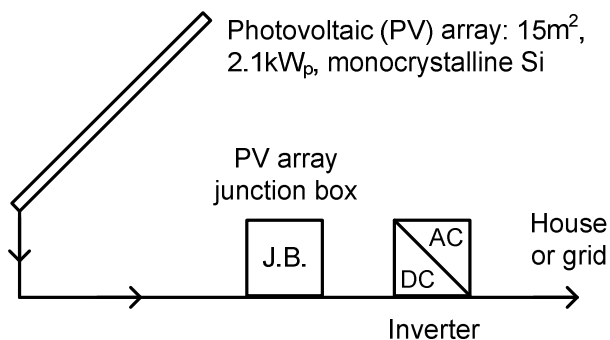


Figure 6-5: Installation schematic of the PV system

#### 6.4.4 Methodology

The methodology followed within this study was as follows:

1. Estimate the electricity output of the PV system for typical UK installations, through a review of the literature;
2. Calculate the solar fraction by incorporating estimates of typical household electricity usage (from Section 4.5), and also estimate the proportion exported rather than being used within the household;
3. Estimate the quantity of upstream energy resource and carbon emissions displaced by solar-derived electricity;
4. Estimate the net energy and carbon performance of the solar PV system.

#### 6.4.5 Results

##### 6.4.5.1 *Estimated annual electricity output*

Two sources were used to estimate the electricity output of the solar PV array outlined in Figure 6-5. One was the recent results of a UK field trial of predominantly crystalline silicon PV modules (DTI 2006b), and the other was the modelling work of a European Commission-supported project that provides mapping of the solar resource and estimation of electricity generation from photovoltaic systems (see Suri et al. 2007).

The UK's 'Domestic Photovoltaic Field Trials' final report (DTI 2006b) analysed the performance of 272 individual PV systems across 17 sites. 81% of the systems comprised crystalline silicon modules, and the remainder were crystalline silicon roof tiles and amorphous silicon roof tiles. The annual outputs of the systems ranged from below 400 kWh/kW<sub>p</sub> to more than 900 kWh/kW<sub>p</sub>, with a modal range 701–800 kWh/kW<sub>p</sub>. All systems with outputs less than 600 kWh/kW<sub>p</sub> had clearly identifiable losses such as long-term inverter outages or high levels of shading, while those below 750 kWh/kW<sub>p</sub> usually exhibited occasional losses due to shading, short-term inverter outages or inverter thresholds (DTI 2006b). In some cases, poor weather conditions have also reduced the output. Only one system, in the South-West of England, gave annual output values over 900 kWh/kW<sub>p</sub>. Interestingly, however, the data sample suggested that location was not a prime determinant of performance; output values were dominated by loss mechanisms and the effect of location did not register comparatively in the analysis. The field trial indicated that many systems were operating 'in line with expectation' and providing annual outputs above 800 kWh/kW<sub>p</sub>. Such a figure therefore seems reasonable as a representative output, but this should be viewed in the context of the wider range of 600–900 kWh/kW<sub>p</sub>. For 13 of the 17 sites the performance ratio (PR; the ratio of the AC electrical output of the actual system to that of an ideal system), was also calculated. The remaining sites had problems with measurements that made the calculation PRs unreliable. The majority of the PRs was in the range 0.65–0.8.

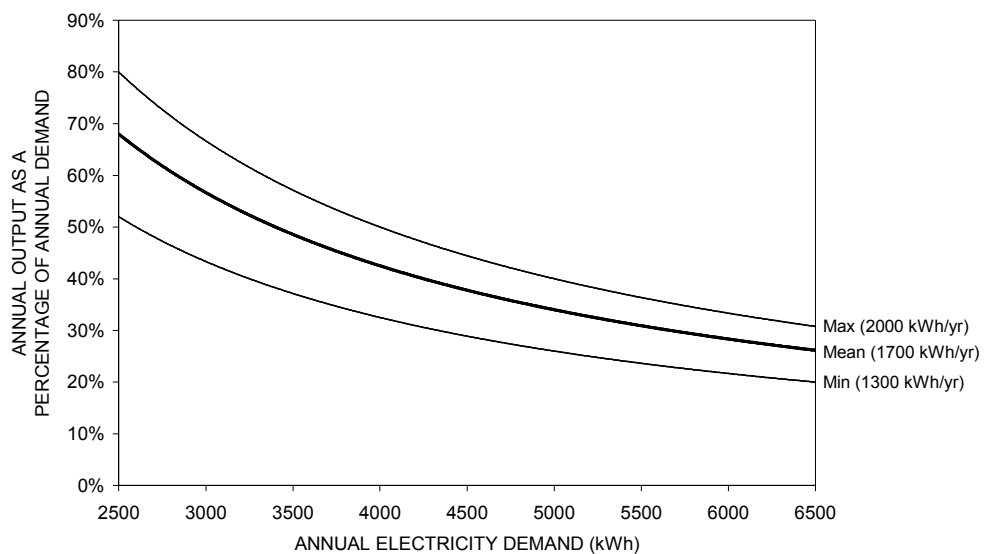
Suri et al. (2007) provide modelling-based estimates of annual electricity generation by a 'standard' 1kW<sub>p</sub> grid-connected PV system. This consists of roof-mounted crystalline silicon modules with a performance ratio of 0.75, and is hence both appropriate for this study and comparable with the field trial results above.

Suri et al. (2007) focused on areas where most people live and where PV is mostly installed, which is urban residential areas in the UK. The overall range of their estimated annual outputs was approximately 620–950 kWh/kW<sub>p</sub>, which agrees roughly with the UK field trial results, while their ‘90% occurrence’ box plot for urban residential areas was approximately 770–900 kWh/kW<sub>p</sub>. Their mean annual output was 820 kWh/kW<sub>p</sub>, which again seems reasonable given the UK field trial results above.

Through combination of the two data sources, the annual electricity output of the 2.1 kW<sub>p</sub> solar PV array was estimated as 1300–2000 kWh (620–950 kWh/kW<sub>p</sub>), with a UK-mean of 1700 kWh (820 kWh/kW<sub>p</sub>). The modal range of the UK field trial (700–800 kWh/kW<sub>p</sub>) was used to estimate a modal output of 1500–1700 kWh.

#### 6.4.5.2 Annual output as a proportion of annual household electricity use

To place the annual output estimates in context it is useful to compare them to the quantity of electricity used by UK households. This is done in Figure 6-6, below, which shows the annual electricity output of the PV array as a percentage of varying annual electricity demands. The minimum and maximum estimated outputs are shown as a representative range, and the mean output is shown as the bold line within this range.



**Figure 6-6: Annual PV output as a percentage of annual household electricity use**

The mean UK output was estimated as 1700 kWh (820 kWh/kW<sub>p</sub>). Figure 6-6 indicates that this is equivalent to 38% of the current mean annual UK household electricity use of 4500 kWh/yr (Section 4.5.3). The type of tariff used within a household has a significant influence on mean annual usage. In 2006 it was 4000 kWh/yr for households with standard electricity tariffs compared to 6200 kWh/yr for households with Economy Seven tariffs (Section 4.5.4). Thus, assuming that the PV array is used by a household with a standard electricity tariff (i.e. not utilising electrical storage heating), the mean electricity output is equivalent to 43% of average annual usage. This percentage reduces to 27% for the mean Economy Seven household.



Section 4.5.4 indicated that the distribution of annual household electricity usage is both broad and positively skewed, and hence the mean usage value is above that of the majority of households. A modal range of 3000–4000 kWh/yr was selected, on the basis of BRE (2005a), to represent this skew, although it was noted that an alternative data sample (Hawkes and Leach 2008) indicated that it could be below this range. The modal PV electricity output of 1500–1700 kWh is equivalent to 38–57% of the modal household electricity demand.

From the preceding discussion it is concluded that the average (mean or modal) PV array outputs the equivalent of 27–57% of an average (mean or modal) household's electricity demand each year. While these may be taken as 'typical' values, Figure 6-6 gives a wider range of percentages on the basis of minimum and maximum PV outputs. Minimum and maximum outputs are equivalent to 21–67% of average annual demands. This is comparable to the UK field trial's (DTI 2006b) sample, which provided solar fractions of between 20 and 80% with a mean of 51%.

It is highly likely that some of the electricity generated by the PV will be exported to the grid (whenever generation exceeds household demand). Bahaj and James (2007) analysed the export ratios of PV arrays installed on a selection of social housing, and suggested that 50% is a typical export proportion (with 70% as a maximum and 25% as a minimum). This agrees with the analysis of the Energy Saving Trust et al. (2005 p.136) who also propose 50% as representative for PV.

#### 6.4.5.3 Energy-resource and carbon savings provided by the solar PV system

The electricity provided by the PV system can reduce the use of the established grid, and thus displace the use energy resources and the emissions of carbon dioxide from that grid. Similar to the case of the micro-wind turbine of Chapter 5, the original work underlying this study assumed that the PV system displaced the 'system-average' grid (Allen et al. 2008a). Section 3.4.6, however, indicated that the PV array would in fact displace 'marginal plant'; plant that modulate their output readily to follow instantaneous (power) demand. A range of marginal ERE and carbon emissions factors was selected, as 2.3–2.9 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.49–0.76 kgCO<sub>2eq</sub>/kWh respectively. Using these factors, Table 5-2 gives the estimates of energy resource and carbon savings enabled by the PV array for differing annual outputs.

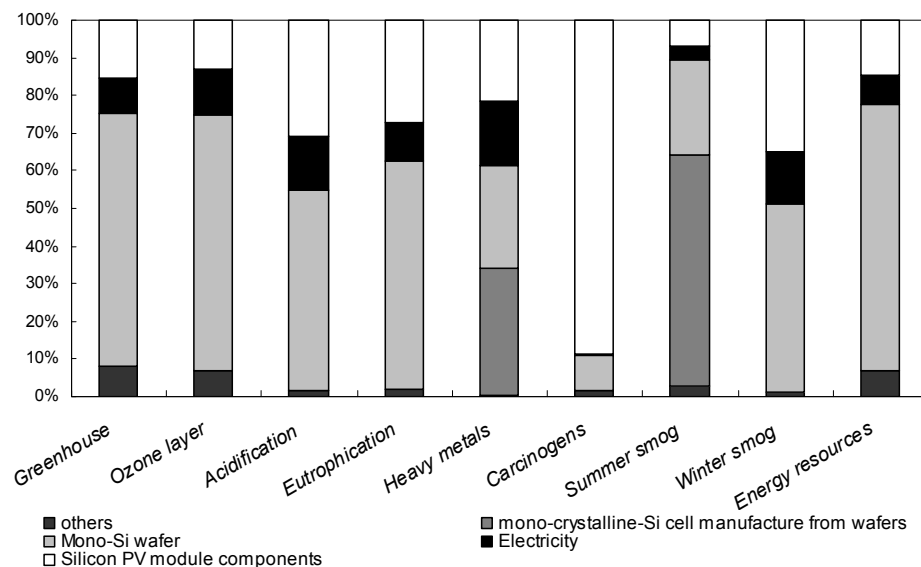
**Table 6-1: Estimates of annual energy-resource and carbon savings provided by the PV system**

	Output (kWh/yr)	Energy-resource saving (MJ <sub>NCV</sub> /yr)	Carbon saving (kgCO <sub>2eq</sub> /yr)
<b>Minimum</b>	1300	10800–13600	640–990
<b>Mean</b>	1700	14100–17800	830–1300
<b>Maximum</b>	2000	16600–20900	980–1500

#### 6.4.5.4 Embodied energy and carbon of the PV system

The net energy or carbon performance of the solar PV system may be estimated by comparing its estimated output (or energy resource/carbon emissions displacement) with its embodied energy or carbon. The latter were calculated as part of a life-cycle assessment undertaken by C. Jones and published as part of the study by Allen et al. (2008a). The work reported within this section also contributed to that publication. The approach taken by the LCA was in general that of 'cradle to operation', which means that life-cycle impacts such as maintenance and disposal were ignored. This was because data was lacking regarding maintenance (though this is expected to be minimal, since PV arrays typically require little maintenance) and disposal. The exception to this was the inclusion of an assumed inverter replacement halfway through the estimated 25 year lifetime of the PV array (Allen et al. 2008a).

The embodied energy of the PV system, plus an inverter replacement, was estimated as 79400 MJ<sub>N<sub>CV</sub></sub>, with an associated embodied carbon of 3760 kgCO<sub>2eq</sub> (Allen et al. 2008a). Figure 6-7 shows characterised production data for this system to outline how different system components contributed to these totals. In contrast to the equivalent micro-wind and solar hot-water studies, the breakdown of PV components is relatively coarse because the data was taken from secondary sources and hence it was more difficult to determine the exact point in the production process from which the impacts arise (Allen et al. 2008a). It is clear, however, that much of the energy and greenhouse gas categories are attributable to the fabrication of the mono-crystalline silicon cell wafers. Further discussion of the environmental impacts of producing the solar PV system may be found in Allen et al. (2008a).

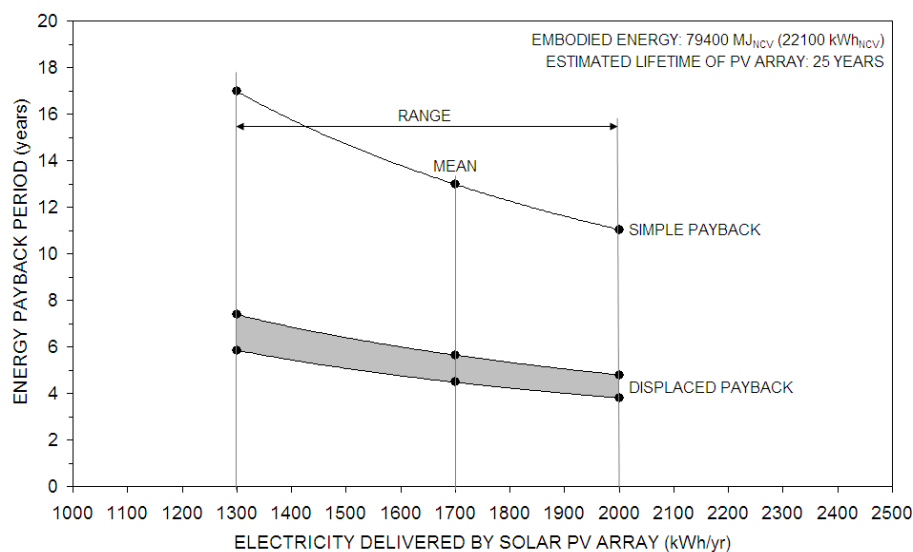


**Figure 6-7: Characterised production data for the solar PV system**

(Source: data from Allen et al. 2008a; calculated by C. Jones)

#### 6.4.5.5 Net energy and carbon analysis

The energy payback period is the time taken for an energy-supply technology to output enough energy to break even with its energy requirement (Section 2.3.7.3). When the electricity output of the PV system is accounted for simply as the units of electricity delivered, as reported at the bottom of Section 6.4.5.1, the *simple energy payback period* (simple EPP) is produced. When the electricity output is accounted for in terms of the total energy-resource displacement, as reported in Table 6-1, the *displaced energy payback period* (displaced EPP) is produced. Both of forms of payback period are summarised in Figure 6-8, below. The displaced payback period is shown as a range (the greyed area), since the marginal ERE of grid electricity is uncertain (Section 3.4.6).



**Figure 6-8: Solar PV system energy payback period for varying annual outputs**

Figure 6-8 indicates that the solar PV system is estimated to produce a quantity of electricity that equals its gross energy requirement in 17 years in the low-output scenario, 13 years in the mean-output scenario or 11 years in the maximum-output scenario. Considering the energy-resource use it displaces from the established grid, the displaced energy payback period is in the overall range 3.8–7.4 years and 4.5–5.6 years in the mean case, depending on the annual output and the marginal ERE of the grid. In all payback cases the PV system pays back within its assumed 25 year lifetime.

Similar to the displaced energy payback period (displaced EPP), a carbon payback period (CPP) can be defined that compares the greenhouse gas (GHG) emissions (communicated in terms of carbon-dioxide equivalent) associated with the production of the PV system with the GHG emissions of marginal plant that are avoided through its use. Similar to the case of the micro-wind turbine, the ratio of carbon to energy payback is fixed, and in this case for any given annual output the minimum carbon payback period is 65% of the minimum energy payback period, and the maximum carbon payback period is 80% of the maximum energy payback period. The displaced EPP values given by Figure 6-8 can be converted to CPPs in this manner. The PV system will thus avoid enough GHG

emissions to break even with the emissions emanating during its production within 5.9 years, and in the mean-output case this will be 2.9–4.5 years.

An alternative net energy indicator is the *energy requirement for energy* (ERE), or in net carbon terms the *carbon-emission factor* (Section 2.3.7.3). These indicators consider the expected lifetime of the PV system, and compare its total energy-resource energy requirement (GER) or carbon emissions to its expected lifetime electricity output. For example, the GER of the PV system is estimated as 79400 MJ<sub>NCV</sub>, and in the mean case it is estimated to output 6120 MJ<sub>e</sub> (1700 kWh) per year for 25 years; a total lifetime output of 153000 MJ<sub>e</sub> (42500 kWh). This gives an ERE of 0.52 MJ<sub>resource</sub>/MJ<sub>delivered</sub>, which means that 0.52 units of energy resource (measured in NCV terms) were sequestered for every unit of electricity delivered to the household or local area by the PV system. EREs and analogous carbon emissions factors for the minimum, mean and maximum output scenarios are shown in Table 6-2, below.

**Table 6-2: Estimates of the ERE and carbon emissions factor of electricity from the solar PV system**

	Lifetime output (kWh)	ERE (MJ <sub>resource</sub> /MJ <sub>delivered</sub> )	Carbon emissions factor (kgCO <sub>2eq</sub> /kWh)
<b>Minimum</b>	32500	0.68	0.12
<b>Mean</b>	42500	0.52	0.09
<b>Maximum</b>	50000	0.44	0.08

The results reported in this section are placed in context in the overall thesis discussion of Chapter 7.

#### 6.4.6 Insights from exergy analysis

Similar to the case of the micro-wind turbine, the gross energy requirement of the PV array will be similar to the gross exergy requirement since the UK's energy system is based largely upon fossil fuels. It has not, therefore, been calculated nor discussed here. Since the electricity output of the PV array has an exergy equal to its energy, the concept of exergy has not been employed to analyse the output of the array either.

## 6.5 THERMODYNAMIC ANALYSIS OF A SHW SYSTEM

### 6.5.1 Introduction

Solar hot-water systems are the most established form of micro-generator in the UK, with approximately 100,000 installed nationwide (Element Energy 2008a). Nevertheless, estimating the energy output of SHW systems for representative households is non-trivial, since there is a complex relationship between the system components and the demand profile of the household it is installed upon. This situation is compounded in the case of this study by the novel aspects of the examined SHW system's design (outlined below). There is also a lack of UK-specific net energy and carbon data for SHW systems (Section 6.2.3). This section therefore estimates the energy output of a SHW system for representative installations and then calculates its net energy and carbon performance. Monthly and annual output estimations are made for the system under consideration, and performance-influencing factors such as household hot water demand are considered. The quantity of gas, oil and/or electricity displaced at the household by the SHW is then estimated, as are the overall energy-resource and carbon-emission savings. These results are then used to calculate the net energy and carbon performance of the SHW system, by incorporation of embodied energy and carbon data.

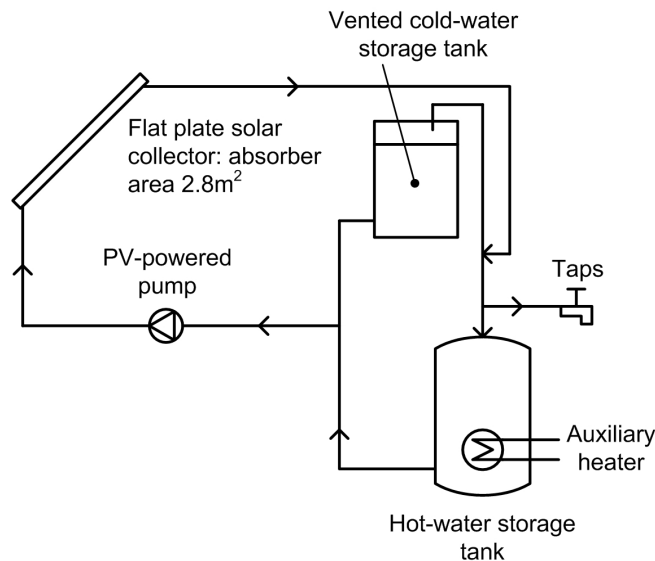
### 6.5.2 Background

Similar to the case of the micro-wind turbine, this study was conducted through collaboration with a UK manufacturer of a commercially-available solar hot-water system. The collaboration provided benefits to both parties; essential real-world data for this research and the dissemination of results to the collaborating manufacturer for their use. Collaboration was conducted via face-to-face meetings and presentations, and through contact via telephone and email. For the purposes of the thermodynamic analysis presented here, this provided an improved understanding of the system studied. The collaboration also provided vital information to the LCA, the most important of which was an inventory of materials and processes used during manufacturing. This is relevant to the following discussion because it led to the calculation, within the LCA, of the gross energy requirement of, and carbon-emissions associated with, the solar hot-water system. An early form of the work was published as part of the study by Allen et al. (2008a), and the more detailed work outlined below (which included multiple auxiliary heating system options, rather than only one) was in preparation for publication at the time of writing of this thesis (Allen et al. 2009).

### 6.5.3 The solar hot-water system

The SHW system examined here is a commercially-available technology comprising a 2.8m<sup>2</sup>, freeze-tolerant, flat-plate collector; typical for installations in 1–4 person households (Solartwin 2006). A novel aspect to the design is that water is provided to the collector by means of a solar photovoltaic-powered pump, which provides a varying flow-rate dependent upon the available solar insolation (for reasons explained in Grassie et al. 2002; a publication investigating an earlier prototype of the system considered here). Another relatively unusual aspect of the design is that it directly feeds the hot water cylinder (rather

than indirectly via a heat exchanger). It is assumed here that this is the household's existing hot water cylinder that is filled by a vented cold water tank, the latter being fed by the mains supply. An existing central heating system provides auxiliary heating to the hot water tank whenever SHW is insufficient to meet demand. Three options for auxiliary heating were considered: a gas-fired central-heating boiler, an oil-fired central-heating boiler, and an electrical immersion heater. Since the existence of the auxiliary heating system and all associated plumbing is independent of the SHW installation (the latter simply reducing the use of the former), the energetic (life-cycle) requirements of the auxiliary system were ignored. The assumed lifetime of the SHW system was 25 years.



**Figure 6-9: Installation schematic of the SHW system**  
(Based on Solartwin 2006)

#### 6.5.4 Methodology

The quantity of hot water provided by a SHW system depends on the user's hot water demand profile, the climatic conditions, and the system's design and performance characteristics. Solar water heating reduces the need to use the auxiliary heating system and hence reduces its use of fuel or electricity, which reduces both upstream energy-resource use and carbon emissions. The net energy or carbon performance of the SHW system can be estimated by comparing the energy provided/saved or carbon saved with embodied energy or carbon, the latter being calculated in the collaborative life cycle assessment. Since the exergy output of solar hot-water system is lower than its energy output, because the output is low-temperature hot water, it may be useful to include the concept of exergy when assessing the performance of a SHW system.

There were thus seven stages to the thermodynamic analysis of the SHW system:

1. Determine residential hot water demand (Section 4.4.2);
2. Determine the (gross) solar resource (Section 6.3);
3. Develop a performance model for the SHW system;
4. Estimate the energy output of the SHW system for typical installations, and the solar fraction this represents;

5. Estimate the energy-resource and carbon saving enabled by the solar-derived hot water;
6. Estimate the net energy and carbon performance of the SHW system;
7. Draw relevant insights from exergy analysis.

#### 6.5.4.1 Residential hot water demand

The hot water usage pattern of a household affects the energy performance of a solar hot-water system, because the temperature of hot water in the storage cylinder affects the net output of the solar collector. If demand is relatively high, the storage tank will be regularly emptied and refilled with cold water, keeping the temperature in the tank relatively low. Conversely, if demand is low, the temperature of water in the storage tank will be higher. A higher tank temperature means a higher inlet temperature to the solar collector, which increases the heat losses from the collector. Thus, lower hot water demands can translate to higher collector heat losses and a lower hot water output. In general, evacuated-tube collectors suffer smaller thermal losses than flat-plate systems and their performance is therefore less sensitive to tank temperatures (DTI 2002b, The German Solar Energy Society 2005).

Section 4.4.2 indicated that the number of occupants in a household is the most significant determinant of daily hot water demand, although it was noted that other factors also have an affect. The average household occupancy in UK households has been slowly decreasing over recent decades, but was broadly constant at approximately 2.4 between 1995 and 2006 (Appendix A). Section 4.4.2 showed that this translates to a daily run-off volume of 110 litres, which in turn equates to an approximate annual hot water demand of 6130 MJ<sub>th</sub> (1700 kWh<sub>th</sub>). This demand is reasonably consistent throughout the year; from a minimum of 440 MJ<sub>th</sub>/month in July to a maximum of 580 MJ<sub>th</sub>/month in January (Figure 4-4).

A recent field trial of solar hot-water systems including the one considered here (DTI 2001b) indicated that, in the case of solar-only storage cylinders, the timing of hot water run-offs during the day has only a small effect on annual SHW energy output. This was a surprising result; energy outputs were similar for both a total run-off at 6pm and for a split run-off over three times: 7am, 12pm and 6pm. Conflicting factors that affect the daily energy output were identified: 'a draw off pattern which requires water early in the morning requires that some hot water is stored overnight, with corresponding losses, but at the same time it gives lower tank temperatures during the day, allowing the collectors to operate more effectively'. The two effects approximately cancelled one another out (DTI 2001b).

#### 6.5.4.2 Solar resource for the SHW collector

The SHW collector considered here has an absorber area of approximately 2.8 m<sup>2</sup>. It is assumed here that the collector is installed on SE to SW facing roof with a pitch angle of 15–50°, and Section 6.3 therefore indicates that the collector will receive 9700–13000 MJ/yr of global irradiation (2700–3500 kWh/yr).

#### 6.5.4.3 *Performance model for the SHW system*

The SHW system considered here was tested as part of a field trial of several commercially-available SHW systems in 2001 (DTI 2001b). The resulting performance model, which correlates daily solar irradiation with daily heat output (a linear relationship) and is valid for daily hot water demands of 150 litres, was used in this study to estimate the energy output of the SHW system for a range of location and installation possibilities. The results of a follow-up field trial (DTI 2002b) indicated how certain factors can affect SHW energy output, of which the effect of reduced daily run-off volume was relatively significant. Since an average, 2.4 person UK household is estimated to use 110 litres per day (Section 4.4.2) rather than 150 litres/day, the follow-up field trial results were used to estimate the change in energy output given this reduced daily run-off volume. There are a variety of advantages and disadvantages to this approach, which are now discussed in turn.

The advantages of using the original field trial's performance model include that it was independently produced and that the loading and climatic conditions were logged and reported alongside energy outputs, the latter of which enabling the estimation of energy outputs for differing solar resources. Whilst previous monitoring reports available in the literature have reported results from systems performing in specific installations, it is not typically possible to generalise those results due to unspecified loading and climatic conditions. Most importantly, however, the DTI trial gives performance of the complete, installed systems rather than collector performance in isolation, which has been the focus of many previous laboratory tests of SHW systems. This is particularly useful in the case of the SHW considered here, because the system has novel aspects to its design (Section 6.5.3) and operation and hence established SHW modelling techniques (e.g. BSI 1989 and BRE 2002) are unlikely to be inappropriate for output estimations.

The primary disadvantage of using the original field trial's model (DTI 2001b) is that it is still constrained to being representative of only certain installations, due to the complex nature of solar hot-water supply and the variety of factors affecting performance. Three of these factors are particularly relevant to the current discussion: combined (rather than separate) storage of hot water from the SHW system and an auxiliary heater; variations in mains-water inlet temperature; and reduced daily run-off volume. All three affect the temperature profile of water in the hot water storage cylinder and this, in turn, can influence the overall energy output capability of the SHW system. Given higher inlet temperatures to the collector, heat losses are greater and hence the net output can be reduced. Each factor was investigated by a follow-up field trial (DTI 2002b). Unfortunately (from the viewpoint of this study), the follow-up trial tested only two of the previous eight systems due to larger experimental resource requirements per system, and this did not include the SHW system considered here. One of the two systems studied was based on a flat-plate collector and the other on an evacuated tube collector. The SHW system considered here uses a flat-plate collector, suggesting the flat-plate results would be most applicable, but involves a different plumbing layout and operational characteristics to the flat-plate system tested in the follow-up trial. In the absence of further data, the effects on both systems were used to indicate a range of possible effects on the SHW considered in this study. For reasons outlined below, the effects of combined storage and variations in



mains inlet temperature were ignored while the effect of reduced daily run-off volume was incorporated.

The original field trial tested the SHW system in combination with an otherwise unheated storage cylinder (DTI 2001b). The SHW considered here, however, feeds directly into an existing storage cylinder in most installations, and this cylinder is also heated by the auxiliary heater (Figure 6-9). The follow-up field trial (DTI 2002b) investigated the effect of 'combined storage' of SHW and an electrical immersion heater, but the results were inconclusive. While auxiliary heating creates higher tank temperatures that can increase heat losses from the collector and hence decrease overall energy output, storage losses are reduced since only one tank is used. Given a highly optimised heating schedule with evening-only run-off, the follow-up field trial suggested that the net effect of combined storage could thus be an increase rather than decrease in output. However, the effects of combined storage with split run-off patterns throughout the day were not quantified. It is possible that as long as the heating schedule is well matched to the pattern of run-off, combined storage could offer equal or even improved performance no matter what the run-off pattern, by topping up to the desired temperature just prior to run-off without leaving high tank temperatures to impinge on the performance of the SHW system. Conversely, however, a poorly-timed heating schedule could have a negative impact on performance due to high tank temperatures during solar charging. Because of this uncertainty, it was assumed that an auxiliary heating schedule would be well-timed by the householder to match their hot water use, and that this would not affect the annual solar energy output significantly. Further research in the area of combined storage with varying run-off patterns is recommended.

The SHW system considered here is assumed to be used in conjunction with a cold water storage tank located in the roof-space of the house (Figure 6-9). The temperature of water entering the solar system is therefore affected by a range of factors, including the ambient temperature, the solar insolation incident on the surface of the roof, the time the water is held in the cold water tank, and the level of tank insulation. Two extreme situations were considered in the follow-up field trial (DTI 2002b): 1) the water temperature would have risen to be the average daily temperature of the ambient air, or; 2) the cold water would be at the temperature of the mains supply. For the two systems studied, estimated annual outputs increased by up to 10% or decreased by as much as 5% compared to the original field trial estimates. However, these estimations were simulations based on extreme cases, and while they quantify such extremes it is unclear whether they are any more likely than the actual cold water inlet temperatures experienced by the SHW systems during testing in the original field trial (DTI 2001b). In fact, the mains inlet temperatures for regular boiler systems in the EST hot water use monitoring report are broadly similar to the inlet temperatures during the first DTI field trial (DTI 2001b; Energy Saving Trust 2008). It was therefore assumed that the estimations based on the original field trial were representative and did not require alteration.

Reduced daily run-off volumes for a given SHW system sizing can reduce the solar energy output for a number of possible reasons. Firstly, low run-off volumes may mean

that less of the solar energy captured during the day is utilised by the householder; a particularly important factor during high insolation months of the year. Instead, hot water would sit in the storage tank and simply lose heat to its surroundings, and although this might provide useful space heating, the quantity of solar-derived hot water utilised by the householder would be a lower proportion of the solar energy that was actually captured. Secondly, reduced run-off may result in higher tank temperatures, which can reduce energy outputs as previously discussed. The effect of varying the daily run-off volume was not quantified during the original testing; it investigated a total daily run-off of 150 litres only. This is a relatively large volume and, using the volumetric consumption model given by the EST study (Section 4.4.2), represents approximately 4 people. As previously discussed the national average occupancy for a UK household is 2.4 people, representing a volumetric daily demand of 110 litres according to the EST model.

The follow-up DTI field trial (DTI 2002b) estimated the effects of reduced run-off volumes for the two SHW systems it studied, and both were found to suffer a reduction in energy output when the daily run-off volume was reduced. For a daily run-off volume of 110 litres, the follow-up report (DTI 2002b, Figure 3.15) indicates that energy output would be reduced by 17% and 9%, for the flat-plate and evacuated-tube systems respectively. These percentage changes were taken in this study as a range of possible effects on the monthly SHW energy output. The values consider only an evening run-off – extracting the whole volume at 6pm – and do not indicate how performance would vary if the run-off was spread across the day. However, the original field trial (DTI 2001b) indicated that the timing of hot water run-offs during the day may have only a small effect on the annual energy output (Section 6.5.4.1). At this juncture, therefore, the reduced-output values were considered representative of split run-off patterns, as specified in the first trial (DTI 2001b) and below in the listed ‘assumptions’, as well for evening-only run-offs.

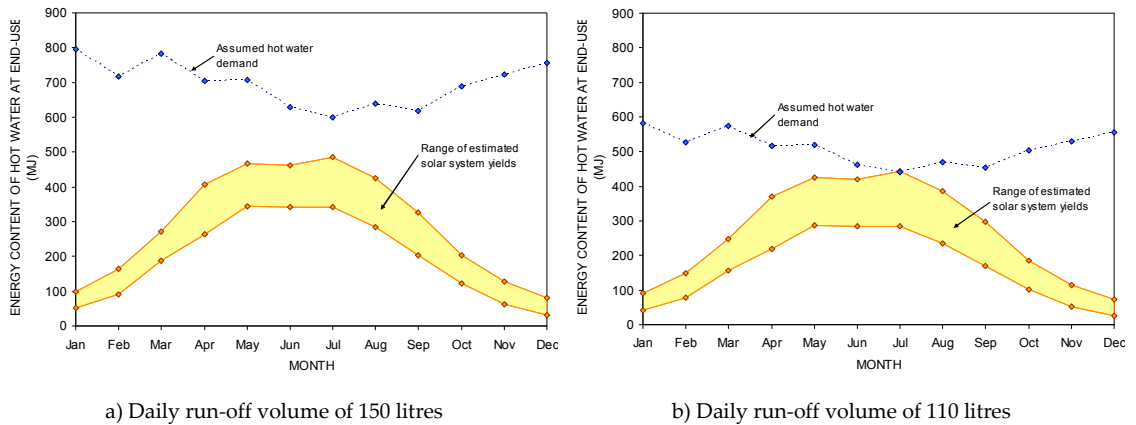
## 6.5.5 Results

### 6.5.5.1 *Estimated energy output of, and solar fraction for, the SHW system*

The original side-by-side test performance model (DTI 2001b) was used to estimate the energy output of the SHW system for a range of geographical positions, azimuths and pitches, and the results are summarised in Figure 6-10a. These estimations are valid for a daily run-off volume of 150 litres/day, which is representative of approximately 4 people. The average UK household occupancy, however, is 2.4 people, for which 110 litres/day is a more likely run-off figure. The results of a follow-up field trial (DTI 2002b) were therefore used to adjust the energy output estimates to represent a daily run-off volume 110 litres/day, and the results are summarised in Figure 6-10b. The '150 litres/day' case is perhaps more reliable, being based on direct experimental data, but less representative of the average UK household occupancy. The '110 litres/day' case is less reliable, being an adjustment based upon the performance of different SHW systems, but more representative of the average UK household.

The following assumptions underlie the energy output estimations:

- The system is appropriately installed in the UK somewhere between Glasgow or Aberdeen and Plymouth. It is unshaded, and facing SE to SW with a pitch of approximately 15 – 50°. This azimuth and pitch represent a typical installation, and will increase the insolation received by the collector by 10–15% compared to a horizontal surface.
- The hot water demand is either 150 litres/day or 110 litres/day, and has the following temperature and timing characteristics:
  - The cold water inlet temperature varies with month, and has an annual average of 16°C. The assumed average monthly temperature values are shown on Figure 4-4, as is the assumed delivery temperature of 53°C throughout the year.
  - The hot water is runoff in one of the following two ways: 1) Entirely at 6pm; or 2) 40% at 7am, 20% at 12pm, 40% at 5pm. These were the two run-off patterns included in the side-by-side test (DTI 2001b). The difference between the two was minimal, but both were considered.
- The solar hot-water storage is combined with the auxiliary-heater storage but with negligible effect (this assumes a well-timed heating schedule; see Section 6.5.4.3).
- Heat losses from plumbing between the collector and hot water tank ('primary pipework'), and tank storage losses, were automatically included in the estimation, as such losses underpinned the performance measurements of the DTI study (DTI 2001b). The length of primary pipework during the DTI measurements was approximately 10m (the equipment enclosure, housing the water cylinder, was 5m from the solar panel).
- Distribution losses (between the hot water tank and the taps) are assumed to be 15% of the energy leaving the tank, in accordance with BRE (2002)



a) Daily run-off volume of 150 litres

b) Daily run-off volume of 110 litres

**Figure 6-10: Estimated useful-energy output of the SHW system**

Figure 6-10 summarises the monthly heat supply and demand at end-use, for daily run-off volumes of both 150 litres (Figure 6-10a) and 110 litres (Figure 6-10b). In Figure 6-10a, the annual hot water demand is 8360 MJ<sub>th</sub>, of which the SHW supplies between 2330 and 3520 MJ<sub>th</sub> – a solar fraction of 28–42%. In Figure 6-10b, the annual hot water demand is reduced by 27% to 6130 MJ<sub>th</sub>, and this is estimated to cause a 9–17% reduction in energy output. The annual output is thus reduced to 1940–3200 MJ<sub>th</sub>, while the solar fraction is increased to 32–52%. In this scenario the SHW output is close to meeting demand during the summer months, and satisfies it entirely during July given the highest estimated hot water output.

Comparison of the estimated outputs of Figure 6-10a and Figure 6-10b indicates that the daily run-off volume has a relatively small effect on output compared to other factors. While the reduced runoff from Figure 6-10a to Figure 6-10b is estimated to reduce output by 9–17%, the minimum output in Figure 6-10a is 34% less than the maximum output, while the minimum output in Figure 6-10b is 39% less than the maximum output. Since this study was interested with the overall range of likely outputs in the UK, the relative influence of location, pitch, azimuth and daily run-off pattern have not been separately quantified here (since space is restricted). Further work could, however, quantify such relative influences.

For the remainder of this section the overall output range is taken as representative of the SHW system; i.e. 1940–3520 MJ<sub>th</sub>. These values will be referred to as ‘min’ and ‘max’ SHW-output scenarios. These values are used to calculate the quantity of gas, oil or electricity displaced by the use of SHW (that is, the quantity of delivered energy that would otherwise have been used to provide 1940–3520 MJ<sub>th</sub> of hot water).

#### 6.5.5.2 Energy-resource and carbon savings provided by the SHW system

The solar energy used displaces (avoids the use of) fuel or electricity that would have otherwise been used by the auxiliary heating system, which in turn displaces upstream energy requirements of that fuel or electricity. By estimating the quantity of onsite fuel or electricity displaced, together with their upstream requirements, the total primary energy

and carbon emissions avoided through the use of SHW may be estimated. This study considers three possible options for auxiliary water heating: a gas boiler, an oil boiler, and an electrical immersion heater, for reasons now outlined.

In approximately 86% of the English housing stock (taken here as a proxy for the UK as a whole due to lack of further data), water heating is provided by a 'conventional' central-heating boiler that also provides space heating (Williams 2006). The majority of central-heating is gas-fired; 87% in 2006 (Utley and Shorrocks 2008). On a national level, therefore, gas is the most likely fuel to be used for water heating. Heating oil, in contrast, is a relatively unpopular fuel in national terms (fuelling 4% of central-heating systems; Utley and Shorrocks 2008). However, the manufacturer of the SHW considered here indicated that oil-fired boilers were a common auxiliary system found in customers households; almost as prevalent as gas-fired boilers (B. Johnston, Solartwin Ltd., 2008, personal communication). This may be due to the more attractive performance of SHW in such a scenario; oil is typically delivered manually to households off the gas-grid, and is a more expensive fuel than gas. Electrical immersion heaters were also considered in this study because they are the second most prominent form of water heating after central-heating boilers, comprising 10% of all water heaters (Williams 2006).

Solar water heating reduces the use of the auxiliary heating system and its associated consumption of fuel or electricity. The losses that the auxiliary system would suffer – primary pipework losses (between the boiler and the storage tank), storage losses, and distribution losses (between the tank and the point of hot water delivery) – must be added to the energy output of the SHW system (Figure 6-10) to give the total energy output required by the auxiliary heater. Dividing this value by the heater's conversion efficiency gives the total energy content of the displaced fuel or electricity. The BREDEM-8 domestic energy model (BRE 2002) was used to estimate the displaced primary pipework, storage, and distribution losses associated with the auxiliary heating system, and they are now discussed in turn.

In the case of a gas- or oil-fired boiler, it was assumed that primary pipework (PP) connecting the boiler to the hot water storage cylinder is insulated and that a cylinder thermostat is present. (In the case of an electrical immersion heater there would be no primary pipework.) The BREDEM model estimates that, for such a scenario, annual PP losses will equate to 1280 MJ<sub>th</sub>. This is an estimate of total annual losses; not the losses displaced by the use of SHW. The PP losses avoided due to SHW were estimated by scaling the total, annual value with the solar fraction. For the 150 litres/day case the SF was estimated to be in the range 28–42% and hence avoided PP losses would be approximately 360–540 MJ<sub>th</sub>. BREDEM is a well established but simplistic model, and the magnitude of PP losses is not related to the hot water demand in this calculation, although it is likely that it would be in practice. For the 110 litres/day case a SF of 32–52% would be achieved, giving a PP loss estimate of 410–670 MJ<sub>th</sub>. The overall range of 360–670 MJ<sub>th</sub> was taken as a range for subsequent calculations.

Assuming 50 mm of factory insulated foam, the BREDEM model estimates that annual storage losses would be 1100 MJ<sub>th</sub> for a 150 litre tank, and 930 MJ<sub>th</sub> for a 117 litre tank (the appropriate size for a demand of 110 litres). Again scaling this with the solar fraction, the overall range of displaced storage losses is 300–480 MJ<sub>th</sub>. The estimation of storage losses is complicated where combined storage is adopted, and further work is recommended in this area to quantify its effect.

Distribution losses are estimated to be approximately 15% of the energy leaving the hot water tank, which is equivalent to 17.6% of the energy leaving the tap (BRE 2002). In the 150 litres/day case 2330–3520 MJ<sub>th</sub>/yr of solar hot-water was estimated to be supplied to the taps, and hence 410–620 MJ<sub>th</sub> of auxiliary distribution losses were avoided. In the 110 litres/day case, 1940–3200 MJ<sub>th</sub>/yr of solar hot-water is supplied, avoiding auxiliary distribution losses of 340–560 MJ<sub>th</sub>. The overall range in this case is therefore 340–620 MJ<sub>th</sub>.

Table 6-3 summarises the minimum and maximum solar hot-water outputs and the minimum and maximum avoided losses reported thus far. This gives an overall range of energy that would not be required from the auxiliary heater, and represents an unshaded SHW collector facing SE to SW with a pitch of approximately 15 – 50°, in locations between Plymouth and Glasgow or Aberdeen, with daily runoff volumes of 110 to 150 litres/day.

**Table 6-3: Maximum and minimum displaced auxiliary energy output (SHW output plus avoided auxiliary losses)**

	Min	Max
SHW output (MJ <sub>th</sub> )	1940	3520
Avoided auxiliary PP losses (MJ <sub>th</sub> )	360*	670*
Avoided auxiliary storage losses (MJ <sub>th</sub> )	300	480
Avoided auxiliary distribution losses (MJ <sub>th</sub> )	340	620
<b>Total avoided auxiliary energy output (MJ<sub>th</sub>)</b>	<b>2940</b>	<b>5290</b>

\* Not included when the auxiliary system is an electrical immersion heater

The totals provided in Table 6-3 must be divided by the heating system efficiency to calculate the fuel or electricity displaced by the SHW system. The conversion efficiency of the auxiliary system depends upon the heating system considered. The UK's Central Heating System Specifications (CHeSS) set out the basic efficiency levels required to meet building regulations, applicable for new boiler installations, and at the time of writing these were last specified in 2005 (Energy Saving Trust 2005a; Energy Saving Trust 2005b). For a domestic central heating system with regular boiler and separate hot water store (the case considered here), the boiler must have a SEDBUK efficiency of at least 86% in the case of gas and 85% in the case of oil (in both cases in terms of the GCV of the fuel). These conversion efficiencies were considered appropriate for the present study. Higher efficiencies are possible (best practice guidelines are for 90% or above), but equally it is possible that the SHW system would be installed alongside an older, less efficient boiler. However, the SHW system has an estimated lifetime of 25 years, during which time a boiler, with a representative lifetime of 15 years, would be replaced by a boiler in line with building regulations at that time (potentially more stringent than those of 2005). Due to

this combination of factors, it was considered reasonable to choose the current minimum CHES standard as appropriate for gas- and oil-fired boilers. In the case of an electrical immersion heater, it was assumed that all electricity is transferred as heat into the storage tank, and hence the conversion efficiency of delivered electricity to hot water in the storage tank is 100%.

Boilers use electricity to power components such as pumps and fans. This electricity consumption must be considered alongside the use of gas and oil in order to give a complete picture of the delivered-energy displacement by SHW. The quantity of electricity displaced was calculated by scaling the annual values for boiler electricity use given in BRE (2005b) by the solar fraction. No such electricity use would be required in the case of an immersion heater.

Table 6-4 shows the maximum and minimum fuel and electricity displacement estimates for each heating-system (gas boiler, oil boiler, and electrical immersion heater). Fuel displacements are presented in NCV terms rather than GCV for consistency with the total energy-resource saving calculations, which are also presented in the table. These latter values were calculated in the collaborative LCA assuming a 'system-average' grid mix for electricity, and then adjusted by the present author in accordance with marginal plant, described in Section 3.4.6.

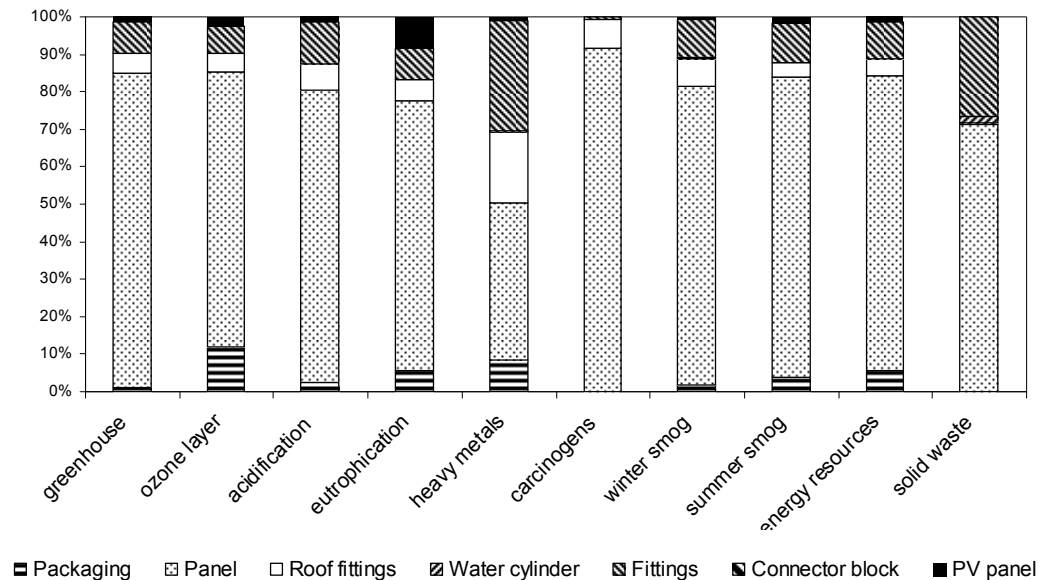
**Table 6-4: Estimates of annual energy-resource and carbon savings provided by the SHW system**

Auxiliary heater	Delivered fuel displacement (MJ <sub>NCV</sub> /yr)		Delivered electricity displacement (MJ <sub>e</sub> /yr)		Total energy-resource saving (MJ <sub>NCV</sub> /yr)		Carbon saving (kgCO <sub>2eq</sub> /yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Gas boiler	3080	5540	150	197	4100–4180	7210–7320	228–239	401–415
Oil boiler	3240	5830	265	348	5090–5240	8870–9070	335–354	585–611
Electrical heater	N/A	N/A	2580	4620	5740–7200	10300–12900	337–526	604–942

The uncertainty associated with the displacement of marginal electricity-generation plant (Section 3.4.6) causes the range of possible energy-resource and carbon savings shown on the right-hand side of Table 6-4. In all cases, the upper end of the margin introduced is likely to be representative of annual savings for a SHW system installed today (strictly, in 2005), whereas out into the future (circa 2020) the values will reduce to the lower end of the margin in each case. There are uncertainties associated with the estimation of marginal plant, however, and hence these maximum and minimum displacement estimations are taken to be an overall range within which actual displacement values are likely to fall over the next 10 or 15 years.

### 6.5.5.3 Embodied energy and carbon of the SHW system

The net energy or carbon performance of the SHW system may be estimated by comparing its estimated output, or the estimated energy-resource/carbon-emission savings, with its embodied energy or carbon. The latter were calculated by Dr. M. McManus in the collaborative LCA, as summarised below. The approach taken by the LCA was that of 'cradle to site', which means that life-cycle impacts after delivery were ignored. This was because data were lacking regarding maintenance and disposal.



**Figure 6-11: Characterised production data for the solar hot-water system**

(Source: Allen et al. 2009)

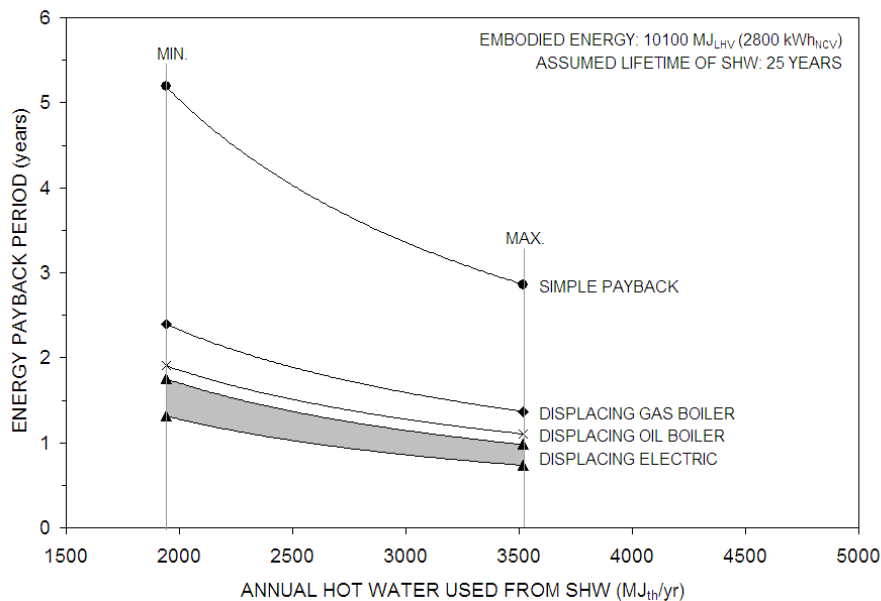
The embodied energy and carbon of the SHW system were found to be 10100 MJ<sub>LHV</sub> and 462 kgCO<sub>2eq</sub> respectively. Figure 6-11 indicates how different components contribute to these quantities. In the cases of both 'greenhouse gas emissions' and 'energy resources' (the gross energy requirement as defined in this thesis), the 'panel' is by far the most significant contributing component to the overall embodied energy and carbon. This is the solar collector as referred to in this chapter and is made of aluminium, which is energy (and therefore carbon) intensive to manufacture (Allen et al. 2009). Further discussion of the environmental impacts of producing the SHW system will be provided in Allen et al. (2009), but were beyond the scope of the present discussion.

### 6.5.5.4 Net energy and carbon analysis

The energy payback period is the time taken for an energy-supply technology to output enough energy to break even with its energy requirement (Section 2.3.7). When the energy output of the SHW system is accounted for as the units of hot water delivered to the end-user, as reported in Figure 6-10, the *simple energy payback period* (simple EPP) is produced. When the electricity output is accounted for in terms of the primary energy displaced, as reported in Table 6-4, the *displaced energy payback period* (displaced EPP) is produced. The displaced EPP is shown as a range in the case of the electrical immersion heater (the greyed area) since the marginal ERE of grid electricity is uncertain. Although this uncertainty also



affects the gas and oil scenarios, since the gas and oil boilers both use small amounts of electricity, the effect is minimal and so is not shown on the figure for simplicity.



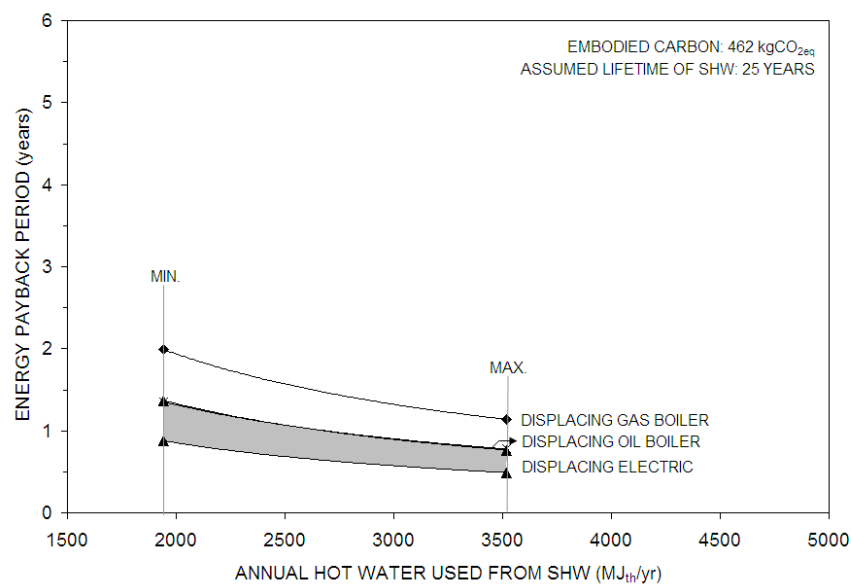
**Figure 6-12: SHW system energy payback period for varying annual outputs and different auxiliary heating-system scenarios**

Figure 6-12 shows the simple payback period of the SHW system and its displaced payback period for each auxiliary-system scenario considered. The minimum and maximum points on the graph correspond to the minimum SHW output and auxiliary system losses, and maximum SHW output and auxiliary system losses, respectively (see Table 6-3). The simple payback period indicates that the SHW system will produce an energy-quantity of hot water equal to its embodied energy in 2.9–5.2 years. This hot water reduces the need to use the auxiliary heating system, assumed here to be a gas boiler, an oil boiler, or an electrical immersion heater. Figure 6-12 shows that when the output of the SHW system is accounted for in terms of the overall energy-resource saving, it pays back within 2.5 years in all cases. It pays back fastest when displacing an electrical immersion heater. The lower end of the range given on Figure 6-12 is likely to be representative of the SHW system installed today, in accordance with the discussion of Table 6-4. The overall range of displaced EPP for the electrical-heater scenario is between 0.8 and 1.8 years depending on the SHW output, the auxiliary system losses, and the marginal generation plant displaced. The displaced EPP is 1.1–2.0 years in the oil-boiler scenario and 1.4–2.5 years in the gas-boiler scenario (in both cases including the range of adjustments due to marginal plant for the boiler's electricity consumption, although not shown on the figure since the adjustments are small – < 0.1 years – and make the figure less readable). In all cases the energy payback period is significantly less than the expected 25 year lifetime.

Similar to the displaced energy payback period (displaced EPP), a carbon payback period (CPP) can be defined that compares the GHG emissions associated with the production of the SHW system with the GHG emissions that are avoided through its use. In addition to energy-related issues, the CPP is influenced by the carbon-emission factor of

the fuel or electricity offset. For gas it is the lowest; Section 3.3.2 indicated a carbon emissions factor of  $0.07 \text{ kgCO}_{2\text{eq}}/\text{MJ}_{\text{LHV}}$ , including amortised life-cycle and upstream impacts of the gas grid. A similarly calculated oil emissions factor is higher;  $0.09 \text{ kgCO}_{2\text{eq}}/\text{MJ}_{\text{LHV}}$ . Both of these are notably lower than the system-average and marginal emissions factor for grid electricity as reported in Section 3.4.6, which converted into MJ terms are  $0.16 \text{ kgCO}_{2\text{eq}}/\text{MJ}_\text{e}$  and  $0.13\text{--}0.20 \text{ kgCO}_{2\text{eq}}/\text{MJ}_\text{e}$  respectively.

The carbon payback times for each auxiliary heating-system scenario are presented in Figure 6-13, below. Again the shortest payback occurs when SHW is displacing an electrical immersion heater, but this time the oil scenario is coincident with the ‘cleanest’ grid-mix scenario (the ~2020 marginal plant mix). In the immersion heater scenario, carbon payback times are in the range 0.5–1.4 years depending on the SHW output, the auxiliary system losses, and the marginal generation plant displaced. In the oil-boiler scenario the range is 0.8–1.4 years, and in the gas boiler scenario it is 1.1–2.0 years, highlighting that gas heating is the cleanest auxiliary heating system in terms of carbon emissions. In all cases these payback periods are significantly shorter than the expected lifetime of the SHW system.



**Figure 6-13: SHW system carbon payback period for varying annual outputs and different auxiliary heating-system scenarios**

An alternative net energy indicator is the *Energy requirement for energy* (ERE), or in net carbon terms the *carbon-emission factor*, of the SHW system. These indicators consider the expected lifetime of the system, and compare its total primary energy requirement (its GER) or carbon emissions to the expected lifetime energy output. The overall range in ERE for the SHW system is  $0.11\text{--}0.21 \text{ MJ}_{\text{resource}}/\text{MJ}_{\text{th}}$  depending on the annual SHW output. The overall range of carbon emissions factor is  $0.005\text{--}0.010 \text{ kgCO}_{2\text{eq}}/\text{MJ}_{\text{th}}$  ( $5\text{--}10 \text{ gCO}_{2\text{eq}}/\text{MJ}_{\text{th}}$ ).

There is an important distinction between these net energy and carbon results and those reported previously for the micro-wind turbine. In the case of micro-wind, the ERE

and carbon-emission factor applied to a unit of delivered electricity; the system boundary was truncated at entrance to the household. The delivered electricity is an intermediate energy carrier that is later employed to provide an energy service within the household, such as lighting, computing, cooking, water heating; each with different end-use conversion efficiencies. In the case within this section of solar hot-water, in contrast, the system boundary was extended to end-use; a defined amount of hot water used within the household (e.g. 110 litres/day at 53°C) that included all losses up to the point of the end-use of hot water. The two net energy/carbon values are not, therefore, directly comparable. The implications of these differences will be revisited in the overall discussion of net energy and carbon results in Chapter 7.

### 6.5.6 Insights from exergy analysis

The discussion thus far has not recognised the thermodynamic quality of the energy provided (as heat) by the SHW system. The micro-wind and solar PV analyses did not explicitly do this either, but that was because the electricity they output has a thermodynamic quality of one – exergy is equal to the energy. That is not the case with the SHW system, and so insights are now drawn from exergy analysis to provide further information for the overall discussion of Chapter 7.

The thermodynamic quality of the heat supplied by a SHW system is dependent upon its temperature relative to that of the environment (as indicated by Equation 2-4; p.27). Monthly data regarding the temperature of the hot water provided by the SHW system were unavailable, and therefore monthly exergy estimations could not be made for comparison with the monthly energy-output estimations. It is possible, however, to infer an annual average SHW delivery temperature, and the following analysis therefore proceeds on an annual basis. The aim of the following discussion is not a full exergy analysis to complement all energy-output estimations, but rather an illustrative example from which to draw general conclusions.

For the purposes of this illustrative discussion, the high-output, 110 litres/day scenario was chosen (the upper bound of SHW outputs on Figure 6-10b). In this case the estimated SHW output was 3200 MJ<sub>th</sub>. Assuming a constant specific heat capacity of water of 4.187 kJ/kgK, an annual average cold water inlet temperature of 16°C, and a volume of 40150 litres (110 litres/day for 365 days), the delivery temperature of the SHW may be estimated via Equation 4-1 (p.67) as 35°C. The overall energy transferred to water in this example is 6220 MJ<sub>th</sub> (assuming a delivery temperature of 53°C), and hence the SHW system provides 51% of the hot water demand. The remaining energy quantity of 3020 MJ<sub>th</sub> is required from the auxiliary heater.

The exergy transfer associated with the heat provided by the SHW system may be calculated via a modified version of Equation 2-3 (p.27). Equation 2-3 must be modified because it applies for heat transfer at constant temperature, which assumes that the source and sink are *thermal reservoirs*. These are systems that remain at constant temperature when energy is added or removed by heat transfer (Bejan et al. 1996 p.46). In cases where the energy source has a finite capacity, however, such as a relatively small body of water,

its temperature will vary during heat transfer. It can be shown (Nieuwlaar and Dijk 1993) that in cases where the source has a specific heat capacity that is independent of its temperature,  $T_p$  (the temperature at the boundary of the heat transfer) can be modelled by the *logarithmic mean temperature*,  $T_{lm}$ :

$$T_p = T_{lm} = \frac{T_1 - T_2}{\ln(T_1/T_2)} \quad 6-1$$

Equation 2-3 therefore becomes:

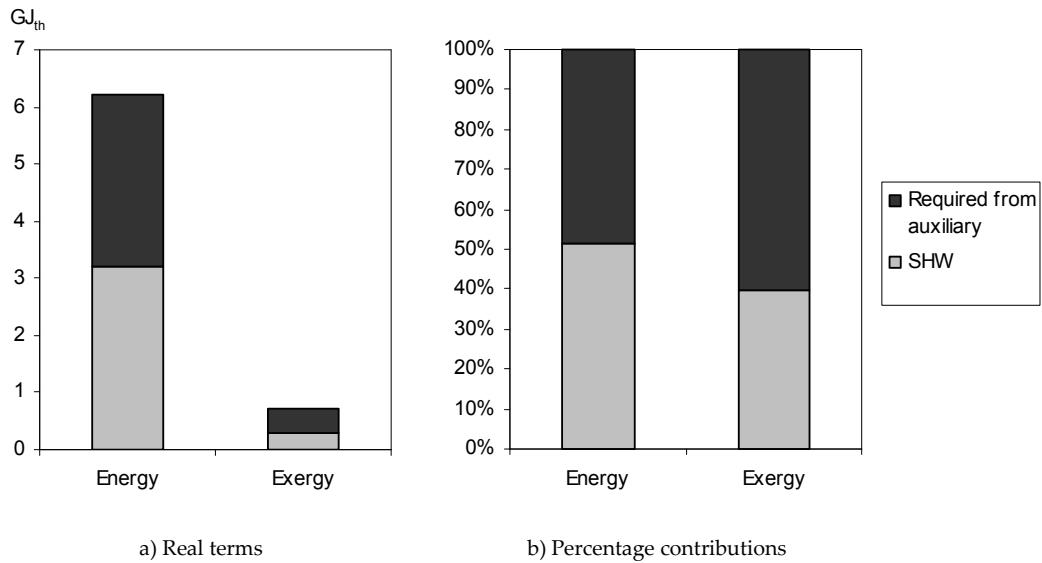
$$E^{Q_p} = \Theta Q_p$$

where:

$$\Theta = 1 - \left( \frac{T_0 \ln(T_1/T_2)}{T_1 - T_2} \right) \quad 6-2$$

where  $T_0$  is the temperature of the environment,  $T_1$  is the cold water inlet temperature and  $T_2$  is the hot water delivery temperature.

In providing 3200 MJ<sub>th</sub> over the year, the SHW system raises the water from 16°C to 35°C (annual averages). Assuming an environmental temperature of -1°C (the typical winter exterior design temperature; Hammond and Stapleton 2001), the thermodynamic quality,  $\Theta$ , is found via Equation 6-2 to equal 0.09 and, multiplying this by the heat supplied equals 280 MJ<sub>th</sub>. Similarly, the overall exergy transfer when raising the water from 16°C to 53°C equates to 710 MJ<sub>th</sub>. The SHW thus provides approximately 40% of the exergy required, and the auxiliary heater would be required to provide the remainder. These exergy results are presented alongside the energy results in Figure 6-14, below.

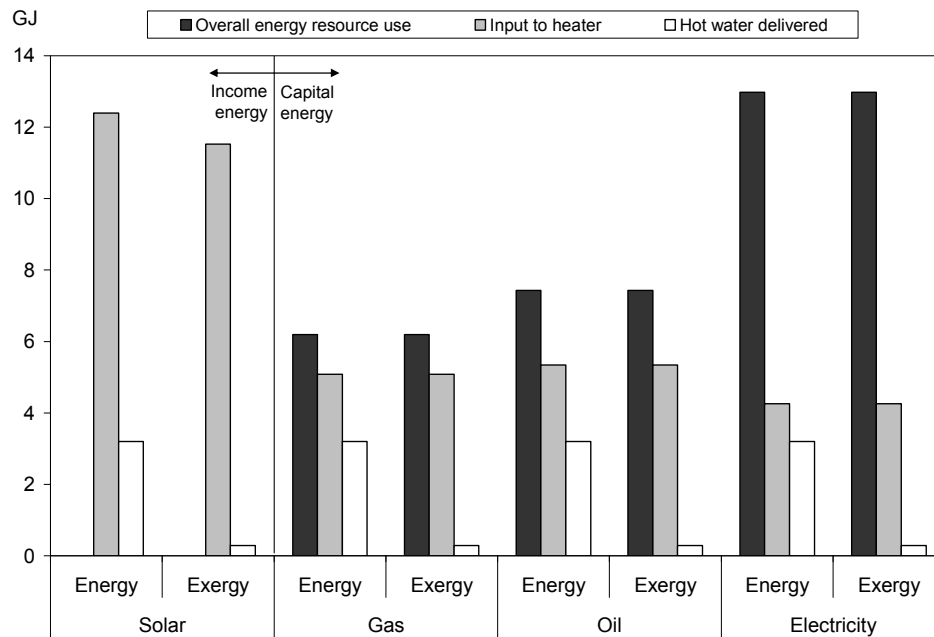


**Figure 6-14: Energy and exergy associated with water heating, showing proportional provision from SHW and auxiliary heater**

Figure 6-14a highlights the significant difference in the energy and exergy requirements of residential hot water. While in energy terms the annual heat demand for hot water is  $6220 \text{ MJ}_{\text{th}}$ , its low temperature dictates that the exergy transferred is only ~11% of this value at  $710 \text{ MJ}_{\text{th}}$  (that is, its thermodynamic quality is 0.11). Figure 6-14b is presented to give greater clarity to the differing proportions of energy and exergy provided by the SHW system. The SHW system provides 51% of the energy demand but 40% of the exergy demand; the remainder in both cases being required from the auxiliary heater. The reduction in relative contribution between energy and exergy is because the lower temperature water provided by SHW is of lower 'value', in exergy terms, than the higher temperature water required from the auxiliary system. In practical terms this highlights the importance of the auxiliary heater; its contribution is important since it is in the higher temperature-portion of the demand and thus required to top-up the water to the desired temperature.

When considering these figures it is important to remember that the energy and exergy supplied by SHW is 'free' (and renewable); its upstream energy requirement is an 'income' flow of solar energy (Section 2.3.3). In contrast, the energy and exergy supplied by the auxiliary heating system (assumed here to be a gas boiler, oil boiler, or electrical immersion heater) have upstream energy requirements that are mostly finite or 'capital' energy resources; primarily fossil fuels. In the context of energy security and carbon-emissions, while both require consideration, it is the depletion of finite fuels that are typically of prime concern.

To highlight this point further, consider Figure 6-15. The case of SHW is shown on the left-hand side, where the white bar gives the heat transferred to the water.  $12.4 \text{ GJ}$  of solar irradiation arrived at the solar collector (the 'heater') during the year to enable this heat supply ( $4.43 \text{ GJ/m}^2$  arriving at a collector of  $2.8 \text{ m}^2$ , which translates to an installation somewhere in the south-west of England). The ratio of energy to exergy for solar irradiation is given by Szargut (2005, in Bösch et al. 2007) as ~0.9, hence the slight reduction between energy and exergy for solar irradiation shown in the figure. The ratio of solar energy input (light-grey bar) to heat supplied by SHW (white bar) gives the energy efficiency of the SHW system, which equates to 26%. Similarly, the ratio of solar exergy input to thermal exergy transfer to water gives the exergy efficiency, which is 2.5%. This shows that there is a large exergy destruction associated with the conversion of solar energy into hot water for the end user, though of course the exergy input was free and renewable.



**Figure 6-15: Energy and exergy assessment of various hot-water supply options**

The right-hand side of Figure 6-15 shows the situation if, instead of the ‘free’ solar input, a gas boiler, oil boiler or electrical immersion are used to provide to same quantity of heat. The electrical immersion heater is the most efficient system within the home, but the overall energy-resource use in this case is much greater due to the large upstream energy losses associated with electricity generation. Gas and oil boilers are preferable in overall energy-resource terms. In all cases, however, there is a large exergy destruction between the input and hot water, since in all cases high-quality fuel or electricity has been converted into low-quality heat. The SHW system thus avoids (prevents) a large non-renewable exergy destruction.

## 6.6 SUMMARY

This chapter has provided estimates of the electricity output of a solar PV system and the heat output of a SHW system. The estimates were placed in context by comparing them with household electricity and water heating demands, and also by estimating the energy-resource and carbon-emission savings they provide. Energy outputs and energy-resource/carbon savings were then compared with embodied energy and carbon quantities to calculate the net energy and carbon performance of the two systems. While the concept of exergy did not provide differing insights in the case of the solar PV system, it has been applied to analyse the output of the SHW system. All results are discussed in the context of other findings in the following chapter.



## CHAPTER 7

# DISCUSSION

### 7.1 INTRODUCTION

The following discussion synthesises the findings of preceding chapters. The main aim of those chapters was to enable and deliver a thermodynamic and related carbon analysis of a selection of micro-generator options for UK households, and the discussion begins with results of those analyses. The other aim of the research underlying this thesis was to contribute to the development and application of a wider integrated appraisal methodology that involved the disciplines of environmental life cycle assessment (LCA) and economic cost-benefit analysis. While some key results will be reported below, it is beyond the scope of this discussion to cover the integrated appraisal in detail. The methodology and its results may be found in Allen et al. (2008a and 2008b), both reproduced in Appendix E.

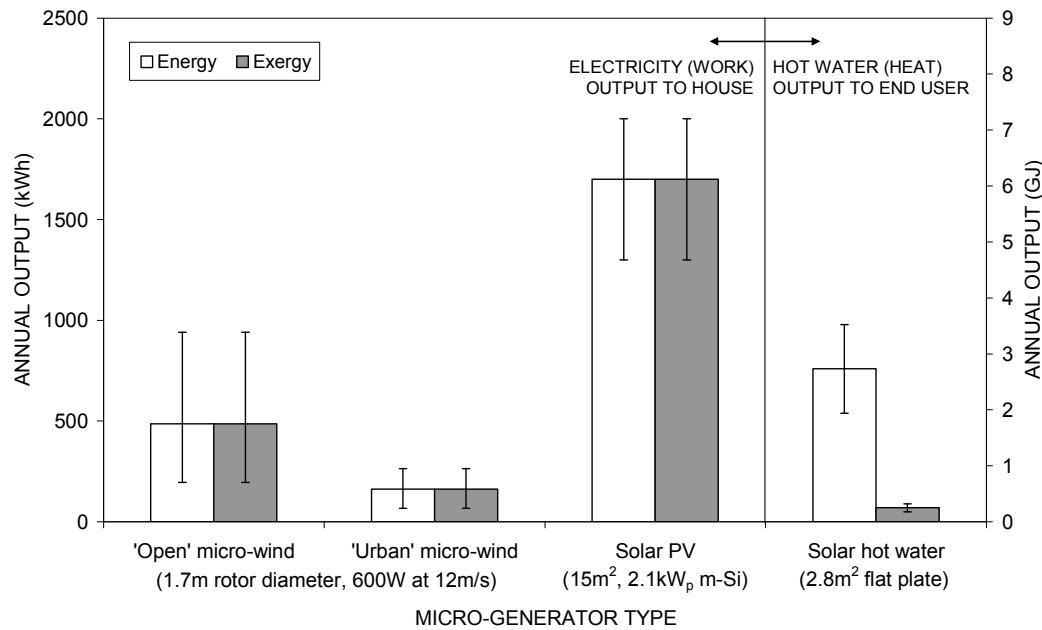
### 7.2 THE MICRO-GENERATORS CONSIDERED

Three micro-generators were analysed in preceding chapters: a micro-wind turbine; a solar photovoltaic (PV) array; and a solar hot-water (SHW) system. The micro-wind turbine and SHW system are commercially-available units, produced by two different manufacturers. The results are specific to those units, and are not necessarily representative of the respective industries more generally. The solar PV system, in contrast, is a generic mono-crystalline silicon system.

### 7.3 ESTIMATED ANNUAL MICRO-GENERATOR OUTPUTS

A key objective of the thermodynamic assessments was to estimate likely annual energy outputs for the micro-generators in appropriate installations across the UK (a complete list of research objectives may be found on p.3). A summary of the more detailed output estimations presented in Chapters 5 and 6 is given in Figure 7-1 overleaf. The white and grey bars represent the energy and exergy outputs respectively. In the cases of the 'open' and 'urban' micro-wind turbine, the heights of the bars denote the mean of the estimation data samples while the error bar range denotes the 5<sup>th</sup> and 95<sup>th</sup> percentile estimates. In the case of the solar PV array, the height of the bar is the mean output given by Suri et al. (2007), while the range given was judged by the author to be representative on the basis of both Suri et al. (2007) and DTI (2006b). In the case of the solar hot-water system, the bar represents the median output estimate of the overall range denoted by the error bars.





**Figure 7-1: Summary of estimated micro-generator annual outputs**

Figure 7-1 shows that the largest annual output is provided by the solar PV system, followed by SHW and micro-wind. The PV system is physically large (compared to the other two) and relatively energy-intensive to manufacture, however, and hence in net energy terms (Section 7.9) its high output is tempered by its larger embodied energy requirements.

Chapter 5 outlined that micro-wind outputs are sensitive to the surrounding terrain and this is indicated on Figure 7-1, since there is a significant difference between 'open' and 'urban' outputs. Power output is proportional to the cube of the wind speed, and wind speed increases with height while turbulent effects decrease. This indicates that it is important to mount micro-wind turbines as high as possible and as clear as possible from wind shadowing and rough terrain. Solar technologies are less sensitive to location. Installation on south-east to south-west facing roofs is preferable to maximise the solar resource (Section 6.3), as is the avoidance of shading effects. But local terrain is generally less important than in the case of wind turbines. While Figure 7-1 and Chapter 5 suggest that the micro-wind turbine would be unsuccessful in urban environments, the solar results apply to any environment given appropriate installation upon a typical roof. The potential market for micro-wind is therefore smaller than for solar technologies, since the U.N. estimates that 90% of the UK population resides in 'urban' environments (Appendix A).

Electricity has a thermodynamic quality of one, and so the exergy outputs are equal to energy outputs for the micro-wind turbine and PV array (see Section 2.4.3, p.26). For the solar hot-water system, however, exergy values are significantly lower than energy values. This is because the energy supplied is relatively low-temperature ( $\sim 35^{\circ}\text{C}$ ) warm water, in the context of an assumed environmental (winter design) temperature of  $-1^{\circ}\text{C}$ . The thermodynamic quality – the idealised proportion of this energy output that could be

available as work – is therefore only 0.09 (Section 6.5.6, p.156). This is a simplistic assessment, because both delivery temperatures and the reference temperature will in fact vary during different days and months, but a more detailed assessment would not alter the general ‘low-quality’ conclusion.

In making any comparisons between the differing output estimations of Figure 7-1 there is an important distinction to highlight regarding the system boundary in each case. The output of the SHW system is hot water actually arriving at the end-user; it is the energy service provided. In contrast, the outputs of the micro-wind turbine and solar PV array are electricity; an intermediary energy carrier that will later be converted into other energy forms to provide various energy services. The micro-wind or PV ‘output’ effectively seen by the householder is therefore dependent upon the conversion efficiencies of the end-use technologies used. An illustrative example can expand on this point. If the electricity provided by the micro-wind turbine is used, say, to heat water via an immersion heater which is then delivered by the associated plumbing system, estimations underlying the SHW analysis of Chapter 6 indicate that this will be achieved with an energy efficiency of electricity to delivered hot water of ~75%. In this scenario the mean open micro-wind turbine would effectively output 1.4 GJ<sub>th</sub>/yr of hot water (from an electricity output of 1.8 GJ<sub>e</sub>/yr) in comparison to the SHW system’s median hot-water output of 2.7 GJ<sub>th</sub>/yr (Figure 7-1). Furthermore, the conversion of electricity into hot water will severely degrade the quality of the energy flow (Section 2.4.3, p.26), and hence the effective exergy output of the wind turbine will be low and similar to that of the SHW system. Although this is a simple example the principles are clear; technology comparisons are more fairly made with equal system boundaries, and the overall performance of energy supply options is dependent upon the ultimate use of the energy via end-use technologies.

There are two further issues to consider when viewing Figure 7-1: the differing energy-output characteristics underlying the annual averages; and the reliability of the different methodologies used to obtain the estimations. Both have implications that require discussion.

## 7.4 MICRO-GENERATOR OUTPUT CHARACTERISTICS

All three of the micro-generators considered thus far are based upon ambient, renewable energy sources: solar energy or its derivative, wind energy. An advantage of this is that the micro-generators have no ‘fuel’ costs during operation (compared to a boiler, for example), but a disadvantage is that they depend upon a variable and uncontrollable source of energy (Appendix C). Although the focus of this research was the determination of aggregate annual performance and related parameters, it is important to highlight some of the issues associated with the variable and uncontrollable nature of the micro-generator outputs.

Both solar and wind resources vary continually, with notable variation across 24 hours and within different seasons. The solar resource is relatively well understood and predictable; it typically peaks during the middle of the day (e.g. Figure 6-4, p.134), and

daily insolation is, on average, around four times greater during summer months than during winter months in the UK (Figure 6-3, p.134). The wind resource is more site-specific than the solar resource due to the significant effects of local obstacles, and it is therefore more difficult to predict for a given location (Section 5.3.4, p.98). Sinden (2007) showed that wind speeds are generally higher during daylight hours (particularly in the afternoon) due to diurnal heating and cooling of the Earth's surface. He also showed that this diurnal effect is accentuated in summer months when daytime heating is strongest, while during winter the diurnal differences are smaller but winds are generally stronger at all times of the day and night.

The continual variability of the micro-generator's energy outputs has important implications for their implementation and use. In the case of the solar hot-water system, an instantaneous match between hot water demand and solar input is not required since the hot water is stored in a tank within the household, but a match between supply and demand must exist within a reasonably short time period (around one day) in most cases. This is because whenever solar-derived hot water remains unused, heat losses from the storage tank will accrue and hence net heat outputs will be lower. Furthermore high tank temperatures, which are partly caused by low demands, can reduce the output of the SHW system by increasing the heat losses from the solar collector (see Section 6.5.4.1, p.144). These factors underlie a common design objective for SHW systems in temperate climates – to meet around 90% of the demand in summer months (The German Solar Energy Society 2005). In such a scenario the solar-output wastage is minimised, and the output per unit area and hence cost-effectiveness is maximised. This principle holds broadly but not precisely true for the SHW output estimates presented in Chapter 6. In the case of a household demand of 110 litres per day, which was estimated to be representative of an average household of 2.4 people, 82–100% of the monthly demand would be met during May–July given the maximum estimated output (Figure 6-10b; p.149). These monthly solar fractions would be reduced 50–64% for the minimum estimated output.

Both the micro-wind turbine and solar PV array are assumed here to be grid-tied and to have no storage facility, and hence any generation that exceeds instantaneous demand will be exported to the grid (if conditions are appropriate). A detailed analysis of the match between electricity generation and demand was beyond the scope of this research, whose focus was upon annual values and related parameters. Nevertheless, Section 4.6 (p.79) indicated that individual household demands can be 'spiky' as a result of many different short-duration loads, and that average households have peak demands in the morning and, more significantly, in the evening. It was also seen that average demands are generally lower during summer than in the winter. Grid-tied solar PV systems are therefore likely to export a relatively large proportion of their electricity particularly during summer months given typical household demands, since their generation is greatest during the middle of the day and particularly during the summer. Bahaj and James (2007) analysed the export:generation ratios of PV arrays installed on a selection of social housing, and suggested that 50% as a typical export proportion (with 70% as a maximum and 25% as a minimum). This agrees with the analysis of the Energy Saving Trust et al. (2005 p.136) who also suggest 50% as representative for PV.

The generation pattern of micro-wind turbines is less predictable than for solar PV, and can occur at any time of the day or night. Since Sinden (2007) indicated that winter wind speeds are higher and have less diurnal variation than summer wind speeds, and since household demands are apparently at their highest in winter months and particularly in the evening, it might be expected that micro-wind turbines would have a slightly better generation-to-demand match than solar PV. There is currently little evidence, however, to prove or disprove this hypothesis, due to the nascent nature of the grid-tied micro-wind industry. Peacock et al. (2008) estimated that 33–55% of the electricity generated by micro-wind turbines of a variety of sizes (encompassing the size considered here) would be exported, which provides tentative agreement with the hypothesis since it is toward the lower end of the range suggested above for PV, but this is by no means conclusive. Further research is required in this area.

The export of electricity onto the network has a variety of technical and economic implications. From a technical point of view, the export of electricity could create a mixture of problems and/or benefits for the network; an issue discussed further in Section 7.11. From the householder's point of view, the financial performance of their investment is influenced by the reward they can or cannot get for exporting electricity. This is a crucial issue for the householder, and although outside the scope of this research further discussion may be found within, for example, Energy Saving Trust et al. (2005); Watson et al. (2006); and Element Energy (2008b).

## 7.5 IMPLICATIONS OF THE DIFFERING ESTIMATION METHODOLOGIES

Along with the differing system boundaries and output characteristics associated with the micro-generation annual output estimations, the reliability of the underlying estimation methodologies must also be considered when viewing Figure 7-1. The estimation methodology varied between each micro-generator because each is operationally distinct, and because the existing literature and available data are different in each case.

The estimation of micro-wind turbine outputs was the most problematic of all three micro-generators because the industry is emergent<sup>12</sup>, field trial data is lacking, and turbine outputs are particularly site-specific since local obstacles have a significant effect on wind behaviour. To deal with these difficulties and provide initial output estimates, a software-based model was written and implemented to take hourly measured wind speeds from a number of manually-selected Met Office weather stations across the UK, and to use these to estimate outputs via the micro-wind turbine's 'power curve' (power output against wind speed), certain inverter characteristics, an estimation of turbulent effects, and a variety of other factors. This approach entails four key issues that require discussion regarding their reliability and associated implications: the weather station selection (and hence data selection) procedure; the power curve's reliability; the treatment of inverter characteristics, and the treatment of turbulence.

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<sup>12</sup> This comment refers to micro-wind turbines for households, particularly in the grid-tied format. Micro-wind turbines are far more established, for example, in the yachting industry.

The twenty-six Met Office weather stations were selected manually on the basis of dataset length, completeness, and to give both a geographical spread across the UK and a mixture of 'open' and 'urban' terrains (Section 5.4.4.2; p.104). Each location was checked approximately with Google Earth (Google 2007), which provided a relatively good visual resolution with which to view the surrounding terrain but of course could not provide detailed information. The standard Met Office exposure for weather station anemometers indicates that the 'open' dataset represents a turbine mounted on a 10m mast in open terrain; i.e. away from the household. This standard exposure is typically impossible for built-up, urban environments. In most of the 'urban' cases, anemometers appeared to be mounted upon flat-topped buildings (according to the approximate location checks with Google Earth). It is likely that the Met Office installed their anemometers to represent, as best as possible, the wind speeds of the local area. It is probable but unverifiable, therefore, that the measured wind speeds are at least as good and probably better than those experienced by a typical urban household. While the dataset collation approach is less preferable than manually checking and/or installing anemometers with the explicit purpose of micro-wind feasibility testing, it has provided an extensive dataset (up to 10 years for each location) with broad geographic coverage, and hence was considered appropriate for initial output estimations. It cannot be guaranteed, however, that the dataset is an ideal representation of the wind resource for open and urban micro-wind turbines.

The second issue regarding the micro-wind output estimations is the use of the manufacturers unverified 'power curve'. There has been controversy regarding manufacturers' published power curves in recent years since they have been produced in different ways and not verified by an independent body (Section 5.3.2). One possible resolution would have been to undertake an extensive testing process to independently verify the power curve within this research, but this was beyond time and resource constraints. The estimations presented here should be viewed with this lack of power-curve verification in mind. The recent publication of the British Wind Energy Association's 'Small wind performance and safety standard' (BWEA 2008b) is likely to improve the power-curve reliability issue, since it requires adherence to the relevant British Standard for power curve production (BSI 2006c). The estimations presented here could thus be iterated within future work with any updated power curves.

Although wind speeds were treated as hourly averages during output estimations, they are in fact continually variable. This causes a continually-varying micro-wind power output, and hence a continually-varying interaction with the inverter. When the wind speed is varying around the turbine's cut-in speed (~2 m/s for the turbine considered here), the turbine may provide short, weak bursts of power. In such a scenario the start-up and shut-down behaviour of the inverter could have a critical effect on net electricity outputs. Such effects were beyond the scope of this research, but it is recommended that further research is undertaken in this area.

Turbulence, including the 'gusting' effect of the air stream, can affect a micro-wind turbine in a number of ways, such as the fatiguing of components and an alteration of the

turbine's energy-capture. Consequently the treatment of turbulence has to be considered with regard to the reliability of the output estimates. It is possible that, since turbulent fluctuations can be associated with excess kinetic energy compared to the energy within hourly mean wind speeds (Healey 1983 in Sheinman and Rosen 1992), turbulent winds could lead to greater electricity generation than smooth (laminar) winds. However, the ability of a turbine to extract any of this extra energy is an area of relatively little empirical knowledge with respect to micro-wind turbines. Since turbulence causes changes in wind direction, and since 'micro horizontal-axis wind turbines' (such as that considered here) need to yaw and face the oncoming wind in order to generate power, it seems likely that turbulence may in fact decrease electricity outputs. Indeed, some industrial practitioners assume this and adopt a measure of turbulence – the *turbulence intensity* – as a heuristic safety factor with which to reduce the output estimations. This approach was adopted here, and turbulence intensities were set as 15% for open turbines and 50% for urban turbines, in accordance with a selection of literature (Section 5.4.4.5; p.108). Adding tentative weight to the magnitude of the latter, and to the 'urban' estimates presented in Figure 7-1, are the results of a recent, small field trial (Encraft 2009 – see Section 5.4.5.1). This trial reported generally low 'urban' outputs and that for four turbines, outputs were 41–71% lower than estimations based on measured wind speeds – a percentage range that encompasses the 50% reduction assumed here.

A further field trial (Sissons et al. 2008), in this case providing detailed data of 100 micro-turbines installed across the UK and operating for a year, was due to report imminently at the time of writing (P.A. James, Southampton University, 2009, personal communication). Further work could therefore compare the field trial results with the output estimations presented in Figure 7-1 (and in more detail in Chapter 5), for validation purposes.

The output estimations for the solar PV system involved no complicated methodology, since conventional silicon-based technologies are relatively well understood and both literature and performance data are more readily available. The results of a recent UK field trial (DTI 2006b) were used in combination with results from a European-wide research project that included estimates of PV performance in the UK (Suri et al. 2007). These two sources display general agreement, though are based upon differing methodologies, and so the range of estimations shown in Figure 7-1 is considered to be a reliable representation of the specified system given an appropriate installation.

The output of a solar hot-water system is affected by a variety of complex factors and, since the system considered here has novel aspects to its design, conventional modelling approaches were unlikely to be appropriate for this research (Section 6.5.4.3). Fortunately, a recent field trial undertook some relatively extensive testing of the system (DTI 2001b). The associated performance model was used here to estimate the system's output for a variety of installation azimuth and pitch angles across the UK. This approach entailed a number of advantages; in particular that the performance model could be used to estimate outputs for a variety of likely installation angles and geographical locations, and that it represents the complete installed system rather than just the collector (Section 6.5.4.3;

p.145). However, the output estimations were still constrained to being representative only of certain installations.

Of particular importance here, in the context of output-estimation reliability, is that the first set of estimations applied to a relatively large daily run-off volume of 150 litres (representative of approximately 4 people), and solar-only hot water storage. This was problematic because an average household will have fewer people – the national average is 2.4 people per household – and hence a lower daily runoff volume, and because the system considered here heats a storage tank that is also charged by the auxiliary heating system. A follow-up field trial (DTI 2002b) that investigated such issues for two other SHW systems, but not the one considered here, was used to inform the first set of estimates. Section 6.5.4.3 thus estimated that a lower daily run-off volume of 110 litres/day – representative of 2.4 people – would reduce outputs by 9–17% while increasing solar fractions (since demand reduced more than output). These estimations are provisional, since they are made on the basis of other SHW systems, but reasonable in the absence of further test data. Because the adjustments are uncertain, Figure 7-1 shows the overall range of both the original output estimations and the adjusted estimations – these will be separated later in this discussion (Section 7.7).

The first set of estimations applied for a separate, solar-only storage cylinder. The SHW system considered here is, however, typically installed to share one storage cylinder with the auxiliary heating system. The follow-up field trial (DTI 2002b) indicated that if the auxiliary heater is well-timed to match demand, the effect on outputs would be negligible. This was therefore the assumed scenario underlying the estimates of Figure 7-1. If the auxiliary heating schedule is poorly timed, and heats the tank at times when the SHW system is operating, SHW collector losses are likely to be greater due to higher collector inlet temperatures and hence net outputs would be lower. A poorly-timed schedule could reduce the outputs shown on Figure 7-1.

It is difficult to compare (and hence validate) the SHW estimates presented in Figure 7-1 with those of other SHW assessments because different published studies often involve differing solar resources, hot water demands, system sizes and so on, all of which affect both output and solar fraction. Nevertheless, the Energy Saving Trust suggests that typical solar fractions are in the range 40–50% (Energy Saving Trust 2006b), which broadly agree with the solar fractions found here of 28–52%. A forthcoming field trial of approximately 100 SHW systems (Bradford 2008) will aid further validation of the estimates presented here, and that is recommended as future work.

## 7.6 ENERGY USE IN UK HOUSEHOLDS

When interpreting the output estimations summarised in Figure 7-1 it is useful to give them context by considering typical household energy demands. Chapter 4 therefore addressed the objective of examining the energy use patterns of UK households, giving historical trends, current average demands, and indications of possible future trends.

Table 7-1, which synthesises data from Chapter 4, shows that since the 1970s the vast majority of energy delivered to UK households has been used for space and water heating. Chapter 4 described a strong trend toward the use of central-heating systems during recent decades, and 91% of households were using such systems by 2006 (Utley and Shorrocks 2008). In the majority of cases these systems are powered by gas boilers, and water heating is also usually provided by the same boiler. This technological shift has been a key factor in increasing the average heating-system efficiency of the housing stock, and has caused a major fuel-switch in the residential sector from solid fuels (mainly coal) to natural gas. The latter is now the dominant energy carrier used in households – it accounted for 69% of all commercial energy delivered to the residential sector in 2006. Fuel switching to natural gas within households has been accompanied by a similar move in the electricity-generation sector and, since gas is a relatively clean fuel, this combination was a key element of the 22% reduction of annual carbon emissions attributable to the residential sector between 1970 and 2004.

**Table 7-1: Summary of delivered energy use by end-use, with time-series trends**

End-use	2006 fuel-split (whole sector)*	Recent mean delivered-energy usage (average household)	Trend
Space heating	84% gas 9% oil 2% solid fuel 5% electricity	45–50 GJ/yr* (13–14 MWh/yr)	Mean usage has been broadly constant since 1970, as both internal temperatures and energy-efficiency levels have increased. Average usage is likely to reduce as temperature levels saturate and infrastructure (e.g. insulation) and end-use technologies (e.g. boilers) continue to improve. According to BERR (2008g) new builds currently require 7 GJ/yr (2 MWh/yr) and houses under the 'Building a Greener Future' initiative could approach zero demand. Feasible improvements for existing buildings could reduce average demand by one-third to 32 GJ/yr (9 MWh/yr).
Water heating	79% gas 7% oil 1% solid fuel 13% electricity	18–19 GJ/yr* (~5 MWh/yr)	Usage decreased by 18% from 1970 levels (BERR 2008e). BERR (2008g) expect this to remain the same in the near future for all building ages. This implies a slight increase in hot water use since average efficiencies (e.g. of boilers) are improving.
Lights and appliances (inc. cookers)	91% electricity 9% gas (all for cooking)	12–13 GJ/yr† (3–4 MWh/yr)	This category has seen by far the strongest growth; an increase of more than 80% from 1970 levels. Consumer electronics and ICT are now the fastest growing sub-categories. Due to the fast moving nature of some sub-categories it is particularly difficult to estimate future trends, but MTP's 'business as usual' scenario suggests average household electricity use will remain roughly constant over the next decade or so. Under a 'feasible product policies' scenario, average use could decrease.

\* Based on BRE modelling in BERR (2008e)

† Based on both BRE and MTP modelling in BERR (2008e)



Table 7-1 indicates that while space heating is the most significant delivered-energy user (40–50 GJ/yr), there is potential to reduce this use through improvements in building infrastructure and heating-system efficiency. Delivered-energy use for water heating, in contrast, is expected to remain approximately constant. In addition to these significant heating demands, some of the ‘lights and appliances’ demand is also for heat (e.g. cooking and tumble drying; Figure 4-6, p.73). In all cases, the energy carriers used – mainly gas and electricity – have a high thermodynamic quality that is significantly degraded when they are used to provide heat at low temperature within the household. To quantify this degradation in quality, Section 4.7 (p.82) carried out an indicative exergy analysis for each end-use category. Focus was placed on space and water heating, since they are the most significant heating end-uses, and it was seen that the average 2006 household heating system has an energy efficiency of 74% but an exergy efficiency of only 13%. There is clearly a large scope for thermodynamic improvement and hence reduced delivered-energy demands for heating purposes.

These results must be dealt with carefully. The majority of the exergy destruction associated with the use of fuels or electricity for low-quality heating is intrinsic to the process; it is a result of the irreversibilities associated with either combustion or heat transfer or both (Section 2.4.5; p.29). This means that there is limited scope to reduce the exergy destruction associated with those processes, and that entirely different processes are required to achieve significant exergetic improvements. Some technologies more effectively match the quality of the supply to the quality of the demand, and hence minimise exergy destruction and maximise the thermodynamic efficiency of the conversion of delivered to useful energy. Electrically-driven heat pumps, for example, use a relatively small proportion of electrical input to extract low-quality environmental heat and upgrade it to a higher quality for household heating. They can therefore significantly reduce the quantity of delivered energy required to provide space or water heating in households.

While the concept of exergy enables a more thorough understanding of energy conversions and hence thermodynamic performance, it often needs to be supplemented by further information. Solar hot-water systems, for example, also suffer large exergy destruction when they use incoming solar energy to provide low-temperature hot water (Section 6.5.6). But solar energy is a renewable ‘income’ energy flow that involves no carbon-dioxide emissions when harnessed. In the context of reducing fossil-fuel use and carbon-dioxide emissions, solar exergy destruction in itself is therefore less of a concern. This would also be true if the electricity from the solar PV system or micro-wind turbine was used to provide heating, though they might be better used in other ways. Where any of these technologies are used instead of fuels or grid-electricity, the excessive destruction of fossil-fuel based exergy can be reduced.

A shortcoming of the above analysis was that, as in much of Chapter 4, energy flows were not traced to the final energy service provided to the end user. The energy service demand *was* described in the case of hot water, but in the cases of space heating, lighting and appliance-use, demands were described at various levels of *delivered* or *useful* energy (defined in Appendix B). That is because the main concern here was to assess micro-

generation technologies, and a full household energy-service assessment was not essential for micro-wind turbine and solar PV analyses in Chapters 5 and 6, since they are assessed as electricity providers rather than energy-service providers. Whilst such assessments provide useful results for the comparison of electricity supply options, the current discussion indicates that the results will need to be viewed carefully if they are used to guide more general energy-system related decision-making, since they ignore the end-uses of electricity. A more complete analysis of energy-service provision is therefore recommended as further work, as this will provide a more thorough basis against which to consider energy supply options.

## 7.7 MICRO-GENERATOR OUTPUTS IN CONTEXT

The estimated outputs of Figure 7-1 can be contextualised by comparing them with representative household energy demands. Given the micro-generators considered here, it is the hot water and electricity use patterns of households that are of particular interest.

In the case of hot water use, an average, 2.4-person household was estimated to use 6.1 GJ<sub>th</sub>/yr at end-use, which comprises 110 litres/day of hot water at 53°C. Chapter 6 estimated that the SHW system would provide 1.9–3.2 GJ<sub>th</sub>/yr when installed on an average 2.4-person household, which is 32–52% of the annual demand. The remainder would be provided by an auxiliary heater. These estimates were based upon adjustments from a field-trial performance model, which originally represented a hot water demand of 150 litres/day (approximately 4 people) that equates to a hot water demand of 8.4 GJ<sub>th</sub>/yr. SHW system output is affected by the hot water demand, and when installed in this original scenario it was estimated to output 2.3–3.5 GJ<sub>th</sub>/yr: 28–42% of the demand. Though the output has increased in this scenario, the hot water demand has increased further and hence the solar fraction – the proportion of demand met by the solar system – has decreased.

The mean electricity demand of all UK households has been 16 GJ<sub>e</sub>/yr (4500 kWh/yr) since the mid-1990s. The type of tariff a household uses has a significant affect on its annual usage. In 2006 the mean household on a standard tariff was 14 GJ<sub>e</sub>/yr (4000 kWh/yr) compared to the mean ‘Economy Seven’ household of 22 GJ<sub>e</sub>/yr (6200 kWh/yr) – it is likely that most of this extra usage is accounted for by night-storage heating. Chapter 4 indicated that the distribution of household electricity usage is positively skewed, which means that the majority of households reside below mean annual values. A modal range of 11–14 GJ<sub>e</sub>/yr (3000–4000 kWh/yr) was determined on the basis of a sample of over 7000 households (BRE 2005a). As indicated by Table 7-1, it is particularly difficult to estimate how electricity demands may change in the future, because of the huge variety of end-uses of electricity. The MTP’s ‘business as usual’ scenario, however, suggests that average household electricity use will remain roughly constant over the next decade or so. Under their ‘feasible product policies’ scenario, average use could decrease.

Average household electricity usage can be used to give context to the electricity output of the micro-generators summarised in Figure 7-1. This was done in greater detail

for both the micro-wind turbine and solar PV system in earlier chapters (Section 5.4.5.2; p.115 and Section 6.4.5.2; p.137) and is only summarised here. Mean outputs were compared with the aforementioned variety of mean electricity demands, and modal outputs were compared with modal demands. This process indicated that the average 'open' micro-wind turbine provides the equivalent of 5–13% of an average (1996–2006) household's electricity demand, while the average 'urban' micro-wind turbine outputs represent 2–5% of average demands. Given the minimum and maximum 'open' micro-wind outputs (Figure 7-1), the percentage range increases to 3–31% of average demands, while the minimum and maximum 'urban' outputs represent 1–9% of average demands. In comparison, the average solar PV system outputs are the equivalent of 27–57% of average annual household demand, while minimum and maximum PV outputs (Figure 7-1) are 21–67% of average annual demands. While these percentages give context to the output estimates, it is important to note that it is highly likely that some electricity would be exported from the household, as discussed Section 7.4.

## 7.8 ENERGY AND CARBON SAVINGS OF THE MICRO-GENERATORS

By providing hot water or electricity to a household, the three micro-generators assessed in this thesis can reduce the use of energy from the established supply systems, and the carbon emissions associated with that energy use. An objective of this research was to estimate these energy and carbon savings.

For the grid-connected micro-wind turbine and solar PV system, the established supply system was assumed to be the electricity network. It was assumed that any electricity exported from the household would be used locally (e.g. another household), with negligible distribution losses. For the SHW system three different established systems were considered: a gas boiler, an oil boiler, and an electrical immersion heater, each with their own upstream supply systems.

The energy displaced by the micro-generators can be quantified at one of two stages. It can be counted either as the delivered energy displaced at the household level, or as the overall energy resources displaced from the established system (e.g. coal in the mine). The delivered electricity displaced at the household by the micro-wind turbine or solar PV system is simple; it is the electricity provided by those generators. The quantity of gas, oil, or electricity displaced by the solar hot-water system, in contrast, was calculated by estimating the plumbing losses and conversion losses that would be occur in each auxiliary heating-system scenario, together with boiler electricity-use where appropriate.

The estimates for the delivered fuel and/or electricity displacement enabled by the micro-generators are summarised in Table 7-2. A mean displacement is given for the micro-wind turbine and solar PV system as this was calculated during analysis. An average value has not been presented for the SHW system because performance was assessed as an overall range for installations across the UK, and average values were not, therefore, generated for the overall energy-resource or carbon saving.

**Table 7-2: Annual energy and carbon savings attributable to the micro-generators**

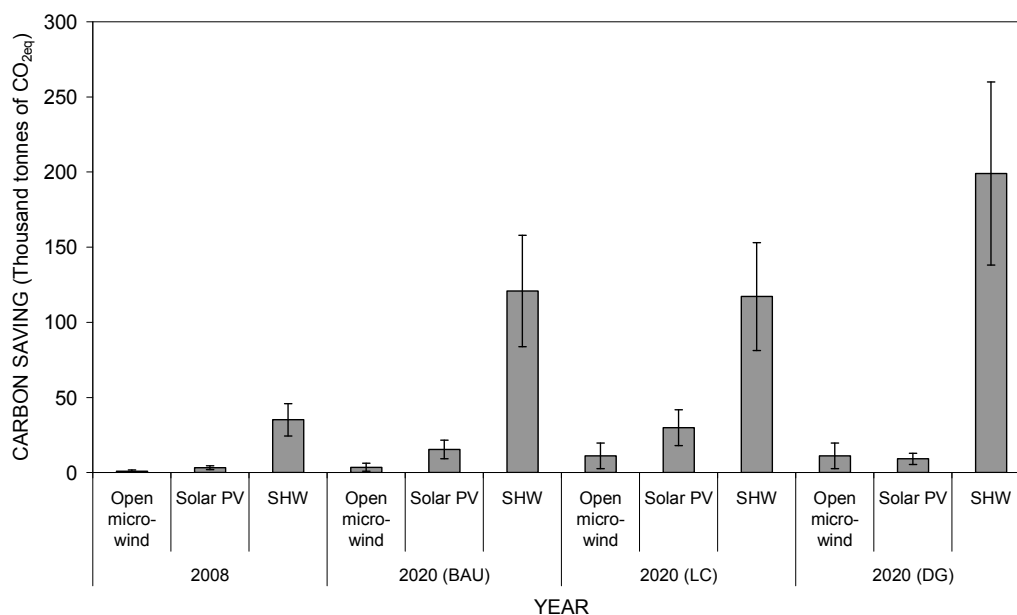
Micro-generator	Key	Delivered elec. displacement (GJ <sub>e</sub> /yr)	Delivered fuel displacement (GJ <sub>NCV</sub> /yr)	Overall energy- resource saving (GJ <sub>NCV</sub> /yr)	Carbon saving (kgCO <sub>2eq</sub> /yr)
<b>Open micro-wind</b>	Overall range	0.7–3.4	-	1.6–9.8	95–714
	(Mean)	(1.8)		(4.0–5.1)	(238–369)
<b>Urban micro-wind</b>	Overall range	0.2–0.9	-	0.55–2.7	33–200
	(Mean)	(0.6)		(1.3–1.7)	(79–122)
<b>Solar PV</b>	Overall range	4.7–7.2	-	11–21	640–1500
	(Mean)	(6.1)		(14–18)	(830–1300)
<b>SHW (gas boiler)</b>	Overall range	0.15–0.20	3.1–5.5	4.1–7.3	230–415
<b>SHW (oil boiler)</b>	Overall range	0.27–0.35	3.2–5.8	5.1–9.1	340–610
<b>SHW (elec. heater)</b>	Overall range	2.6–4.6	-	5.7–13	340–940

During discussion of Figure 7-1 it was highlighted that the boundary conditions were different in the case of the SHW system. This difference is resolved in Table 7-2, since the SHW system is now described in terms of the delivered energy, or total energy resource, it displaces instead of the hot water provided. The relative performance of the SHW system has increased, since there are inefficiencies suffered by the auxiliary heating systems that are credited to the SHW system. Another distinction within Figure 7-1 (p.162) was the difference between the energy and exergy delivered by the SHW system. Now that the effect of the hot water has been traced up to the level of the delivered energy displaced from the auxiliary systems, this difference is not present since the energy and exergy of electricity or fossil fuels are similar.

Table 7-2 indicates that the greatest annual energy-resource and carbon savings are enabled by solar PV, which would be expected since it has a large electricity output and because the established electricity system is relatively energy and carbon intensive. The SHW system displaces the most energy and carbon when installed alongside an electrical immersion heater, and the least when installed alongside a gas boiler (since this is the most resource-efficient auxiliary system). The carbon savings enabled are significant quantities. They can be given context by considering that the residential sector as whole, constituting approximately 26 million households, emitted 42 million tonnes of CO<sub>2eq</sub> in 2004 (DEFRA 2007). The mean household was therefore responsible for the emission of approximately 1600 kgCO<sub>2eq</sub>. The carbon savings enabled by the mean open wind turbine are, for example, approximately 15–23% of this value.

To provide an indicative estimate of the carbon savings enabled by each type of micro-generator at a national level, the individual savings of Table 7-2 can be scaled up by either known or predicted UK installed numbers of each type of micro-generator. This assumes that the savings shown in Table 7-2 are representative of the micro-generation technologies in general. For the year 2008, installed numbers were taken from Element Energy (2008a). To indicate savings that could be achieved by 2020, estimates of installed numbers were taken from the three scenarios developed and described by Jardine and Ault (2008): 'Business as Usual' (BAU); 'Low Carbon' (LC); and 'Deep Green' (DG). The annual savings

estimated for the residential sector as a whole are given in Figure 7-2, below. The error-bar ranges on Figure 7-2 reflect the (overall) range of estimated carbon savings in Table 7-2, while the height of the bar is the median value. It was assumed that only 'open' micro-wind turbines are used, since Chapter 5 indicated their better performance relative to 'urban' turbines. For solar hot water, it was assumed that the majority of SHW systems displace modern gas boilers, as these are predominant in the housing stock (Section 6.5.5.2), while a minority of SHW systems displace oil boilers and electrical immersion heaters.



**Figure 7-2: Annual carbon savings across the residential sector in 2008, and in 2020 under the three scenarios of Jardine and Ault (2008)**

Although solar PV provides the greatest carbon saving per system (Table 7-2), Figure 7-2 shows that SHW systems provided by far the most significant carbon savings of the three technologies in 2008. This is due to their much greater installed numbers – approximately 100,000 SHW units compared to 2,000–3,000 each for micro-wind and solar PV (Element Energy 2008a). Under all three SUPERGEN scenarios – even 'Business as Usual' – savings from the three micro-generation technologies are expected to increase substantially by 2020, with SHW providing the majority on the basis of significant installation numbers. From total savings of between 27 and 52 thousand tonnes of CO<sub>2eq</sub> in 2008, the increase in savings is estimated as approximately 350–360% for 'Business as Usual', 380–410% for 'Low Carbon', and 550–560% for 'Deep Green'. Further information regarding the scenarios, including the different assumptions underlying the trends shown in Figure 7-2, may be found in Jardine and Ault (2008).

The estimates of the total energy-resource or carbon saving enabled by micro-generators are estimates of their effect on the wider energy system. There are uncertainties associated with such effects. In the case of the gas or oil systems the effect of a reduction in demand is relatively straightforward, since the majority of the overall energy resource-use and carbon emissions reduction is at the level of the household. The *average* energy-

resource requirement and carbon emissions associated with each unit of gas or oil was therefore deemed sufficient for estimating savings. These values were found to be 1.2 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.24 kg of CO<sub>2eq</sub>/kWh for gas, and 1.4 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.33 kgCO<sub>2eq</sub>/kWh for oil.

Chapter 2 showed that the situation is more complicated when a micro-generator displaces electricity from the established supply system. When a micro-generator provides a unit of electricity to a household it does not displace the *average* generation mix. Rather, it displaces certain *marginal* generation plant that respond to fluctuations in demand. The estimation of which marginal plant will be displaced by a micro-generator, and hence what the energy-resource and carbon saving will be, is a non-trivial calculation. In this thesis the results of some peer-reviewed modelling work (Bettle et al. 2006), which had estimated marginal carbon-emission factors out into the near future, were taken and adjusted to incorporate previously-excluded life-cycle emissions and transmission/distribution losses. *Energy requirement for energy* (ERE) values were also estimated to enable an energy-resource saving estimate. To enable these estimations, a simplifying assumption was made here that marginal plant are a mixture of only coal and gas-fired plant, as implied by the Carbon Trust (2007) and because they apparently do the majority of the load-following on typical days (Section 3.4.3). The two scenarios generated from Bettle et al.'s results were that the marginal plant-mix was either 50% gas and 50% coal, or 98% gas and 2% coal. The disparity is due to an expected shift away from coal and towards gas out to 2020, based on DTI (2000). The resulting range for marginal carbon-emission factor was found to be 0.76–0.49 kgCO<sub>2eq</sub>/kWh, while the associated marginal EREs were 2.9–2.3 MJ<sub>resource</sub>/MJ<sub>delivered</sub>. These values underlie the savings shown in Table 7-2 and in Figure 7-2. If marginal plant do indeed decarbonise out to 2020, the carbon savings shown in Figure 7-2 for electricity micro-generators in 2020 are likely to be at the lower end of the ranges given.

The marginal carbon-emission factors estimated during the process summarised above are within the range used by other published literature. For comparison, the highest marginal carbon-emission factor found was ~0.9 kgCO<sub>2eq</sub>/kWh, which assumes that coal is the displaced plant, while the lowest was found to be 0.43 kgCO<sub>2eq</sub>/kWh, which assumes that combined-cycle gas turbine is the displaced plant (Section 3.4.6). Neither values include (amortised) life-cycle emissions of displaced plant, and both are likely to be overly simplistic since both coal and gas are known to be used as marginal plant, rather than either in isolation (Carbon Trust 2007). The range used here is therefore reasonable for the present work, as are the associated marginal EREs. It is recommended, however, that further work investigates the impact that micro-generators will have on the carbon emissions and energy-resource use associated with electricity supply.

Another related area for further work concerns the likely non-linear energy-resource and carbon savings effect of micro-generators with increasing penetration levels. If a large number of electricity micro-generators were to be installed on homes, significant technical changes would be required on the grid. It is likely that this will affect the marginal plant mix, and the energy and carbon requirements of network adaptation would probably need to be amortised over the responsible micro-generators in some way. The figures quoted

above are valid for penetration levels that would cause a reduction in electricity demand of approximately 0.5–5% per annum, since this was the level modelled by Bettle et al. (2006).

It should be stated here that the possibility of *Jevons' Paradox* (the 'rebound effect') has been ignored in this study. This idea – that energy-efficiency improvements will increase rather than reduce overall energy use – was first put forward by the British economist William Stanley Jevons in 1865 (Sorrell 2009), and has since been the subject of an ongoing debate regarding effective energy policy. For example, does the installation of micro-wind turbine affect the behaviour of the householder, who begins to use more electricity since they perceive that some is 'free'? The effect of Jevons' Paradox on the overall energy or carbon saving effect of micro-generators is an area of little empirical knowledge and thus it has been excluded here. The possibility, however, requires consideration if micro-generators are to be used effectively on a large scale as a method of reducing fossil-fuel use and carbon emissions.

## 7.9 NET ENERGY AND CARBON ANALYSIS OF THE MICRO-GENERATORS

A major reason for interest in micro-generation technologies is their potential to reduce carbon-dioxide emissions and enhance energy security by reducing use of, and dependence upon, fossil fuels. For the micro-generators assessed here to achieve this they need to repay their (fossil-fuel dominated) energy and carbon investments within their lifetimes and then continue to provide useful energy from their ambient energy sources. This concept underlies the technique of net energy analysis, but although it has been developing since the 1970s, there is a lack of application to micro-generation technologies, particularly in the context of the UK. Net carbon analyses of micro-generators are similarly scarce. A key objective of the research underlying this thesis was, therefore, to contribute such information to the literature.

While the 'net energy' and 'net carbon' principles are simple, it has been seen within this thesis that their calculation is not, and hence such analyses must be communicated and interpreted carefully. A critical element of a net energy or carbon analysis is a clear definition of the system boundary, as this sets the scope of the study and thus influences the results. Since this research was concerned with the total resource use and carbon emissions associated with different micro-generation technologies, the system boundary was effectively drawn around the Earth: energy flows were traced back to their natural state. The only exception to this was ambient renewable energy sources, which were accounted for once they have been converted into useful (e.g. electrical or thermal) energy (Section 2.3.3; p.13).

Alongside the boundary to which energy flows are traced, a net energy/carbon analysis should also clearly specify which life-cycle stages have been included in the study. The studies reported here were, in general, 'cradle-to-operation' – they excluded life-cycle stages such as maintenance and disposal. The exception to this was an assumed inverter replacement during the solar PV array's lifetime. The life-cycle truncation was necessary because the systems studied have little data available regarding their maintenance and

disposal. Maintenance *was* included in an early micro-wind turbine assessment (published as Allen et al. 2008b), since typical-maintenance estimates were made, in this case, by the manufacturer. It was then excluded to ensure consistency with the subsequent solar technology assessments, which did not have maintenance information, and the results for the gross energy requirement of the turbine were very similar. Maintenance is therefore a negligible part of the life-cycle impact of the micro-wind turbine. It is likely that this would be the case with the two solar technologies, since both are simple technologies with few moving parts, but that was not assumed here and maintenance was thus excluded from all net energy/carbon analyses presented here.

The exclusion of disposal is more problematic, though some comments may be made. In the case of the micro-wind turbine and SHW panel, a large part of the life-cycle impact is due to use of aluminium. Since aluminium is amenable to recycling, it is likely that the devices could be used to reduce the life-cycle impacts of subsequent technologies. The EcoInvent database used by Allen et al. (2008b), for example, estimates that to produce 1 kg of virgin aluminium currently takes 201 MJ<sub>NCV</sub> whereas to produce 1 kg of recycled aluminium takes only 23 MJ<sub>NCV</sub>. Energy requirements and carbon emissions associated with the disposal of these micro-generators could, therefore, be partially recouped, in the sense that future technologies would have lower production impacts. Crediting any future recycling savings to the micro-generators is a debatable procedure, however (e.g. Hammond and Jones 2008), and has not been undertaken here. Further research is recommended to consider the sensitivity of the results presented here to different disposal scenarios.

The variation in energy and carbon payback periods for the micro-generators were discussed in detail in preceding chapters, and so are only summarised here, for comparative purposes, in Table 7-3. Similar to the summary of energy and carbon savings presented above, mean values are presented for the micro-wind turbine and solar PV array since they were calculated during analysis, but only an overall range was calculated for the SHW system. The mean micro-wind and solar PV results have ranges for the displaced energy and carbon payback period because the exact energy and carbon displacement is uncertain, as discussed above.



**Table 7-3: Energy and carbon payback periods of the micro-generators**

Micro-generator	Key	Simple energy payback period (years)	Displaced energy payback period (years)	Carbon payback period (years)	Assumed lifetime (years)
<b>Open micro-wind</b>	Overall range (Mean)	1.5–7.1 (2.8)	0.5–3.1 (1.0–1.2)	0.4–2.9 (0.8–1.2)	15
<b>Urban micro-wind</b>	Overall range (Mean)	5.2–20 (8.5)	1.8–8.9 (2.9–3.7)	1.4–8.5 (2.3–3.5)	15
<b>Solar PV</b>	Overall range (Mean)	11–17 (13)	3.8–7.4 (4.5–5.6)	2.5–5.9 (2.9–4.5)	25
<b>SHW (gas boiler)</b>	Overall range	2.9–5.2	1.4–2.5	1.1–2.0	25
<b>SHW (oil boiler)</b>	Overall range	2.9–5.2	1.1–2.0	0.8–1.4	25
<b>SHW (elec. heater)</b>	Overall range	2.9–5.2	0.8–1.8	0.5–1.4	25

Table 7-3 shows that, in ‘simple’ payback terms, all micro-generators payback their energy investment within their lifetime with the exception of the poorest performing urban micro-wind turbine. The simple energy payback period (EPP) compares the output of the micro-generator directly with its energy ‘debt’ (its embodied energy). This means comparing either electricity or hot water with the gross energy requirement of the micro-generator. The boundary condition is different for the SHW system: its output is the useful energy provided at end-use (the hot water out of the taps), in contrast to the electricity generators who supply an interim energy carrier. The displaced EPP, in contrast to the simple EPP, compares the technologies with equal boundary conditions. It accounts for all three micro-generator outputs in terms of the energy-resource displaced from the appropriate established supply system. The carbon payback period is similarly calculated. Once these payback periods have been reached, the micro-generator will begin to provide a net energy or carbon benefit compared to the situation if it had not been used. Displaced payback periods thus communicate whether or not the net effect of the micro-generators is a reduced dependence on established energy resources and carbon emissions. This is a key piece of information, since it underlies a major source of interest in micro-generation.

The displaced energy payback periods and the carbon payback periods shown in Table 7-3 are well within the lifetimes of the micro-generators – they do indeed provide a net energy and carbon benefit. The urban micro-wind turbine displays the poorest performance since its electricity output is small, but its small output would probably make it unviable anyway. The fastest displaced payback occurs in the case of the ‘open’ micro-wind turbine, which in the best case pays back within approximately half a year. The shortest payback for the solar hot-water system occurs when it is installed alongside an electrical immersion heater, and the longest is when installed with a gas-fired boiler. This is because, per unit of hot water delivered, grid electricity is the most energy and carbon intensive. While the solar PV array provides the greatest amount of energy to the end-user, it also has the largest embodied energy and carbon. The net effect of this is that its energy and carbon payback periods are the longest (excluding urban micro-wind) – they are in the range 2.5 to 7.4 years compared to less than 3.1 years for all cases of open micro-wind and

SHW. The paybacks for solar PV are, however, still small relative to its expected lifetime of 25 years.

Another net energy indicator calculated in this research is the *Energy requirement for energy* (ERE) – the quantity of energy resource (at the extent of the system boundary) sequestered for each unit of energy delivered over the life-cycle of the technology in question. It thus incorporates the expected lifetime of the device into the calculation (longer lifetimes will equate to higher energy outputs and hence lower EREs), and it may also be compared to the established supply systems. The ERE has an analogous indicator for carbon dioxide emissions – the *carbon-emission factor*. Both are shown on the left of Table 7-4, which also includes indicators for an average and marginal unit of electricity from the grid, and an average unit of delivered natural gas and oil.

**Table 7-4: ERE and carbon emissions factors for the micro-generators**

Micro-generator	Key	At arrival to the household		Within the household at end-use	
		ERE <sup>a</sup> (MJ <sub>resource</sub> /MJ <sub>delivered</sub> )	Carbon-emission factor <sup>a</sup> (kgCO <sub>2eq</sub> /kWh)	GER per unit of hot water at end-use <sup>b</sup> (MJ <sub>resource</sub> /MJ <sub>delivered</sub> )	Carbon emissions per unit of hot water at end-use <sup>b</sup> (kgCO <sub>2eq</sub> /kWh)
<b>Open micro-wind</b>	Overall range	0.10–0.47	0.02–0.10	0.13–0.63	0.03–0.13
<b>Urban micro-wind</b>	Overall range	0.35–1.36	0.07–0.28	0.47–1.81	0.09–0.37
<b>Solar PV</b>	Overall range	0.44–0.68	0.08–0.12	0.59–0.90	0.10–0.15
<b>SHW</b>	Overall range	N/A	N/A	0.11–0.21	0.005–0.010
<b>Electricity from grid</b>	Mean	3.05	0.58	4.06	0.77
<b>Marginal plant</b>	Overall range	2.3–2.9	0.49–0.76	3.07–3.87	0.65–1.01
<b>Residential gas</b>	Mean	1.22	0.24	1.94	0.38
<b>Residential oil</b>	Mean	1.39	0.33	2.32	0.55

a. Affected by upstream conversion, transmission and distribution losses (as well as life-cycles of the technologies and supply systems in question)

b. Affected by end-use efficiency, end-user behaviour, etc.

Table 7-4 indicates that electricity from the micro-wind turbine or solar PV array is associated with much lower energy-resource use or carbon emissions than electricity from the established grid. This is primarily because they generate electricity from ambient renewable sources of energy in contrast to the established grid, which depends heavily on fossil fuels. A direct comparison is not, however, strictly valid, since the assumed micro-generator installations rely on the network when operating. Electricity is exported to the grid when it exceeds demand, and is imported from the grid with the micro-generator output is lower than demand. Furthermore while marginal plant can follow fluctuations in load, the micro-generators assessed here cannot, at least given current configurations. The micro-generators are not, therefore, a direct substitute for the grid. Nevertheless, their output is significantly less energy-resource and carbon intensive, and hence it appears that they can indeed reduce dependence on fossil fuels and reduce the carbon emissions associated with electricity.

As highlighted previously, there is an important distinction between the electricity micro-generators and the solar hot-water system. Electricity is an intermediate energy carrier that is used within the household to provide a wide array of energy services, whereas the hot water supplied by the SHW system is the final energy service. For this reason the SHW system has no 'ERE' or emissions factor that can be directly compared with the micro-generators or established fuel and electricity supply systems – hence the exclusion from the appropriate columns of Table 7-4. Instead, the figures are of the final energy service provided – the gross energy requirement (or emissions factor) of a unit of hot water. To enable comparison between SHW and other technology options, it was assumed that the latter are used to provide hot water within the household. This required assumptions regarding the end-use technologies that would be used within the household to convert the various energy carriers (electricity, gas, oil) into hot water. This was done during the research underlying Chapter 6. For a modern gas or oil boiler, the overall conversion of fuel into hot water was achieved with an efficiency of 63% and 60% respectively. This conversion efficiency was 75% in the case of the electrical immersion heater. These efficiencies were used to calculate the gross energy requirement (GER) and carbon emissions factor of a unit of hot water at end-use, and the results are shown on the right-hand side of Table 7-4.

The difference between the left- and right-hand sides of Table 7-4 illustrates the importance of considering end-use when comparing the net energy performance of different technologies providing different forms of energy, since it increases all energy and carbon figures of all options except those of the SHW system. It also indicates that the solar hot-water system generally offers the least energy-resource and carbon intensive way of providing hot water to an end-user. All three technologies (SHW, micro-wind and solar PV) perform better than the established systems although, as discussed, direct comparison is not strictly valid. Table 7-4 also makes it clear that if fossil fuels are to be used, it is far more energy and carbon efficient to provide heat with them directly rather than via electricity.

The net energy and carbon results present in Tables 7-3 and 7-4 can be compared with the results of other published literature reported in the introductory sections of Chapters 5 and 6. Net energy results will be discussed here without net carbon results for simplicity, since the conclusions are similar in each case. There are difficulties in comparing studies because differing boundary conditions, assumptions, and geographical regions often apply, but nevertheless a broad pattern can be detected. The micro-wind results presented here add weight to the conclusion of Lenzen and Munksgaard (2002) that larger wind turbines generally perform better in net energy terms. The results they present, together with the large-turbine studies of Krohn (1997) and Martínez et al. (2009), have better net energy results than those presented above for the micro-wind turbine. The mean ERE from Lenzen and Munksgaard (2002), which was based upon more than 70 published studies of mainly medium and large-scale turbines, was  $0.06 \text{ MJ}_{\text{resource}}/\text{MJ}_{\text{delivered}}$ , with a mean displaced payback period of 0.4 years. The EREs calculated by Krohn (1997) and Martínez et al. (2009) were  $0.02\text{--}0.04 \text{ MJ}_{\text{resource}}/\text{MJ}_{\text{delivered}}$  with paybacks less than 0.4 years. In comparison, the open micro-wind turbine analysed here was found to have an ERE of  $0.10\text{--}$

0.47 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and a displaced payback period of 0.5–3.1 years, while the urban micro-wind turbine had an ERE of 0.35–1.36 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and a displaced payback period of 1.8–8.9 years.

The micro-wind results reported here are similar but generally better, in the ‘open’ case, than the two micro-wind turbine analyses reviewed in Section 5.2.4. Rankine et al. (2006) reported displaced paybacks of 1.5–6.2 years, while Celik et al. (2007) reported a displaced energy payback of 1.4 years in the best case. In contrast, the mean open wind turbine of Table 7-3 pays back in 1.0–1.2 years, in the wider overall range of 0.5–3.1 years. The overall variation in the results reported both here and by Rankine et al. (2006) and Celik et al. (2007) highlight that net energy (and carbon) performance is sensitive to the wind resource. All displaced payback periods are, however, within the estimated lifetimes of the turbines.

The net energy results for the solar PV system are again comparable with existing literature. The overall range of displaced payback period reported here was 3.8–7.4 years, while in the mean case it was 4.5–5.6 years. In comparison, Bennett (2007) concluded that 5 years is a ‘good conservative estimate’ for monocrystalline systems installed today. Alsema et al. (2006) suggested a shorter payback of 2.7–3.5 years for middle-European countries, and that there are ‘clear prospects’ for embodied energy reductions that could reduce this to within one year in the near future. It is important to point out that the embodied energy values used in this work are based on the same inventory data used by Alsema et al. (2006) – the one published by Wild-Scholten and Alsema (2005). The poorer performance exhibited here is likely, therefore, to be due to lower estimates for electricity outputs. Tovey and Turner (2008), who also recently used the inventory data published by Wild-Scholten and Alsema (2005), found energy payback periods similar to those reported here: 6.4 years for mono-crystalline systems and 7 years for poly-crystalline.

The SHW system results are comparable but generally better than those reported by Bennett (2007). He reviewed eleven LCAs of solar water-heating systems, none of which were from the UK. He then adjusted the results to estimate UK performance and concluded with a displaced energy payback period of 2.0–3.8 years. In comparison the overall range of displaced payback periods reported here is 0.8–2.5 years (Table 7-3).

In summary, the net energy results are broadly similar to those reported elsewhere in the literature. Net carbon results are also similar, although not repeated above. The overall number of studies for micro-wind and the solar technologies is relatively small, and hence the results presented here provide useful further information to the literature. Although there are uncertainties associated with the calculation of net energy and carbon performance, this combined evidence suggests that all three technologies assessed here, and their technology categories in general, can provide significant net energy and carbon benefits given appropriate installations. It is recommended that further net energy and carbon studies are undertaken to corroborate or contradict this hypothesis.

## 7.10 THE WIDER INTEGRATED APPRAISAL

The research reported in this thesis was undertaken as part of a wider ‘integrated appraisal’ process that also involved environmental life cycle assessment (LCA) and economic cost-benefit analysis (CBA). They can be viewed as being ‘integrated’ in the sense that they are interconnected, but yield differing insights regarding the uptake of micro-generators (Allen et al. 2008a). Both energy analysis and LCA avoid the examination of products on a ‘sub-system’ basis, in which only one part of the life-cycle is examined. Instead they aim to examine the total impacts associated with a product or service, an important step when aiming to develop more sustainable energy systems.

Energy analysis and LCA are interrelated in the sense that energy analysis was one of the precursors to LCA, and the calculation of the *gross energy requirement* is typically now performed in parallel in most modern LCA software (Hammond and Winnett 2006). That was the case in this research. Through collaboration with manufacturers (in the cases of micro-wind and solar hot-water) or literature (in the case of solar PV), inventories of materials and production processes were collated by the LCA researchers. These led to the calculation of the gross energy requirement of the micro-generators, which was taken as an input to the net energy and carbon analyses summarised above. At the same time, the energy-output estimations reported in this thesis were passed to the LCA researchers in order for them to examine various ‘in-use’ impacts of the micro-generators. Finally, the range of environmental impacts calculated through collaboration of the energy analysis and LCA were passed to the CBA, in order to calculate the environmental costs in monetary terms.

While a detailed discussion of the other elements of the integrated appraisal and their results are beyond the scope of the present discussion, some key results can be summarised here to give context to the energy- and carbon-focused results of this thesis. Further information may then be found in Allen et al. (2008a). The LCA found that the impacts associated with the micro-wind turbine and solar hot-water system were mainly due to the aluminium that comprises many of their components. This material has a high strength-to-weight ratio but it also gives rise to heavy metals, carcinogens and some types of smog, as well as requiring significant energy inputs during its production. The LCA therefore recommended the use of recycled aluminium wherever possible, since this can reduce those impacts. The solar PV system had the most significant environmental impacts of the three micro-generators, mainly during the fabrication of the silicon cell wafers, but these are offset by its higher energy production. All three micro-generators, given appropriate installations, provided a net benefit for all environmental impact categories considered.

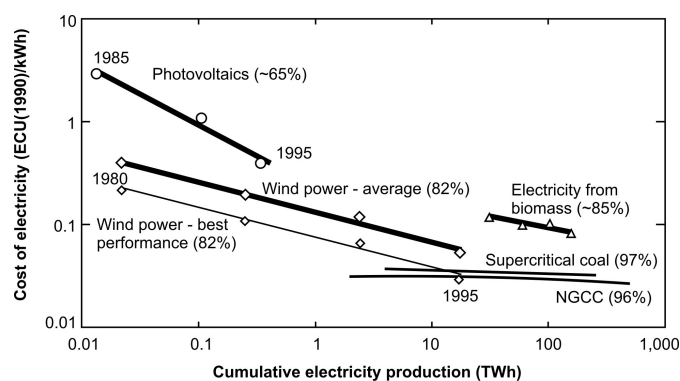
A major driver of the interest in micro-generation is its potential to reduce greenhouse gas and other pollutant emissions, but these ‘externalities’ are not accounted for in traditional economic analyses. Externalities, however, can have economic costs, including social-damage costs. Certain pollutant emissions can, for example, affect human health and incur costs for treatment of illness, or reduce crop yields and thus reduce agricultural revenues. Many of the most significant ‘external’ impacts, such as carbon emissions and other airborne pollutants, were therefore quantified in monetary terms and internalised

within the collaborating environmental CBA to provide a more thorough economic picture of the micro-generators. This process found that, even with externalities accounted for (as described by Allen et al. 2008a), the micro-generators are uncompetitive in the current UK market. The cost-benefit ratio, which indicates the return for every £1 invested, was found to be 1:0.40 for the mean open micro-wind turbine, 1:0.41 for the mean solar PV array, and 1:0.35 for the median-output solar hot water system, and none of the technologies were found to pay back within their lifetimes (Allen et al. 2008a). These economic results apply to the specific systems studied, and do not necessarily represent the technology-types in general.

### 7.11 PROSPECTS FOR AND BARRIERS TO MICRO-GENERATION IN THE UK

The poor economic performance of the micro-generators assessed here is in stark contrast to their positive energy and carbon results reported. Economic barriers were identified as significant for microgeneration in general during earlier research underlying this thesis, which examined the prospects for and barriers to micro-generation in the UK in the period 2006–07 (Allen et al. 2008c). Though outside the main thrust of this thesis, certain elements of the work provide useful context to the results reported above.

From the householder's perspective, high capital costs and low financial returns from energy-bill savings do not encourage the adoption of micro-generation technologies. And with low production volumes, manufacturers generally need to maintain high capital costs. Such a situation is a common barrier to entry for new technologies competing in an established marketplace, and contributes to the 'lock-in' of incumbent technologies (Foxon 2003). As Chapter 3 showed, the established gas and electricity supply systems have been developing for a century or more, and Foxon (2003) indicates that these systems have benefited from long periods of increasing returns that reinforce their dominance. Cost reductions for new technologies do tend to occur, however, as production volumes increase; a phenomenon reflected by *experience curves* and illustrated in Figure 7-3 for a variety of electricity generating technologies in the EU. Photovoltaics, for example, have exhibited significant cost reductions during 1985–1995 according to Figure 7-3. The causes of cost reduction vary, but can include learning-based improvements and economies of scale (Allen et al. 2008c).



**Figure 7-3: Experience curves for EU electricity-generation technologies, 1980 – 1995**  
(Source: IEA 2000)

It appears that stronger Government support is required to encourage the uptake of micro-generation beyond its current position as a niche energy-supply option, and hence enable cost reductions through larger production volumes. A thorough investigation of Government policy regarding micro-generation is beyond the scope of this discussion, although Allen et al. (2008c) looked at recent (2006–07) policy in more depth. Prominent themes at that time were that micro-generation policy lacked coherence and that stable, consistent and long-term frameworks are required to stimulate the levels of investment needed for significant cost reductions – stability that is lacking for micro-generation. As this thesis was being written, the relatively new ‘Department of Energy and Climate Change’ had recently published, with the Department of Communities and Local Government, a consultation document for their forthcoming ‘Heat and Energy Saving Strategy’ (DECC 2009). Government is currently considering the design of feed-in tariffs that would provide financial reward for micro-generated electricity. Such tariffs can provide longer-term support for generators and are advocated by some as a durable method of encouraging micro-generation (e.g. Watson et al. 2006). DECC (2009) are also looking at new finance mechanisms for renewable heat supply. This is a sign that economic barriers may be more effectively addressed in the near future, though this is uncertain at the present time.

In addition to economic barriers, micro-generation faces a variety of technical and information-related barriers that need to be addressed if widespread uptake is to occur. A major technical issue regarding electricity micro-generators is integration with the network, to which the current discussion will now briefly turn. Further issues regarding the prospects for and barriers to micro-generation may then be found within Allen et al. (2008c).

A prevalent configuration for electricity micro-generators is to be connected to the main network via an inverter, as assumed for the electricity micro-generators examined in this thesis. But the current electricity system was designed for centralised generation, as outlined in Chapter 3, and thus optimised for one-way power flow from few sources to many loads (Burt et al. 2008). In the short to mid-term, there is some indication that a reasonable penetration of micro-generators could be incorporated into the existing network. Thomson and Infield (2007), for example, estimate that voltage rise on low-voltage distribution systems is unlikely to constrain solar PV in the short to mid-term – up to a penetration level of 30% of households with PV. In the longer-term, however, network adaptation will be required if distributed generation technologies such as micro-generators are to contribute significantly to the energy mix. Jardine and Ault (2008) created a set of three scenarios in order to examine the consequences of large penetrations of micro-generation in the context of significant (60%) cuts in carbon-dioxide emissions by 2050. They concluded that a future involving significant numbers of micro-generators – where perhaps one third of electricity comes from distributed sources – presents significant challenges in terms of reverse power flow on networks, load balancing, storage requirements, phase unbalance, harmonics and ancillary services (Jardine and Ault 2008). There are thus many technical challenges that preclude a significant use of micro-generation. Among the ongoing research into these issues is that of the SUPERGEN

'Highly Distributed Power Systems' Consortium, to which the research in this thesis contributes. For further information the reader is referred to some recent publications of this consortium, brought together in a special issue of the Journal of Power and Energy, published by the UK's Institution of Mechanical Engineers (see Burt et al. 2008).

## 7.12 LIMITATIONS OF THE ANALYSES IN THIS THESIS

The analyses presented in this thesis (and as part of the integrated appraisal; e.g. Allen et al. 2008a) have not generally traced energy flows all the way to the final energy services desired by end-users, but rather to interim stages of *delivered* or *useful* energy (definitions in Appendix B). This was because the initial objectives of the research were to examine the energy performance of micro-generators as a supply option, and energy-demand analysis took a secondary role mainly to give context to the estimated micro-generator outputs. The energy services ultimately provided by energy-supply technologies are, however, crucially influenced by end-use technologies and infrastructure through their design and energy/exergy conversion efficiencies. These issues became increasingly apparent during the course of this research, and it is recommended that decision or policy-making that aims to reduce dependence on fossil-fuels and the associated carbon emissions should consider, in some detail, the nature of energy demands and end-use technologies alongside the performance of supply options. When undertaking such a 'whole system' approach it is also recommended, on the basis of the insights drawn from exergy analyses and discussed within this chapter, that the concept of *exergy* could be usefully employed alongside that of *energy* to assess the potential for improvement in the energy system.

A further limitation of the research reported both here and by the integrated appraisal as a whole is the extent of the methodological scope. In all cases the energy system is reduced to specific quantities of interest, such as energy or exergy quantities in the case of thermodynamics. But energy systems involve many complex socio-economic, political, and technical interactions, all of which are outside the scope of thermodynamics and most of which are outside the scope of the integrated appraisal. This means that while the results generated here (and by the integrated appraisal) can provide useful information for energy-system decision-making, they must be supplemented with insights from other disciplines.





## CHAPTER 8

# CONCLUSIONS AND RECOMMENDATIONS

### 8.1 RATIONALE

The term *micro-generation* refers to a range of small-scale technologies for localised heat or electricity supply. Micro-generators have the potential to reduce greenhouse-gas emissions and enhance energy security by providing heat or electricity from either renewable sources, or via the more efficient use of fossil fuels. Many are of a size suitable for households and hence there is significant interest in their application to the residential sector – a sector that accounts for approximately a third of the UK's delivered-energy use and carbon emissions. Indeed, several studies suggest that micro-generation has an essential role to play if significant (60–80%) carbon-emission reductions are to be achieved within the sector by 2050 (Johnston et al. 2005; Shorrock et al. 2005; Boardman et al. 2005; Natarajan and Levermore 2007; Boardman 2007). There are, however, numerous barriers constraining the widespread uptake of micro-generation including, crucially, a lack of quantitative information regarding various aspects of practical performance. This thesis has addressed this need for information – information that is vital for uptake to be both appropriate and effective in the context of more sustainable energy provision, and for barriers to such uptake to be reduced.

### 8.2 MEETING THE OBJECTIVES OF THIS THESIS

Three micro-generators suitable for household energy provision have been analysed within this thesis: a grid-tied micro-wind turbine (diameter 1.7m, rated power 600 W at 12 m/s), a grid-tied solar photovoltaic array (15 m<sup>2</sup>, 2.1 kW<sub>p</sub> mono-crystalline silicon), and a solar hot-water system (2.8 m<sup>2</sup> flat-plate collector, direct-feed system). The micro-wind turbine and solar hot-water (SHW) system are specific, commercially-available units, and the results are not, therefore, necessarily representative of the technology types in general. The solar photovoltaic (PV) system is, in contrast, a generic mono-crystalline silicon system.

In order to achieve the twin aims of conducting thermodynamic (and carbon) analyses of these micro-generators and developing and applying the integrated appraisal methodology, a number of inter-linked objectives were specified in Section 1.4 (p.3). The following paragraphs outline how these various objectives have been met.

A key objective for the micro-generator assessments was to estimate their annual outputs in both energy and exergy terms. The exergy output of the electricity micro-generators (the micro-wind turbine and solar PV system) is the same as the energy output, as indicated by its thermodynamic quality of one. The solar PV array was found to provide the largest quantity of energy on an annual basis, providing 4.7–7.2 GJ<sub>e</sub> of electricity per year for appropriate installations across the UK, with a mean of 6.1 GJ<sub>e</sub>. For eighteen 'open' (well-exposed, mostly rural) locations across the UK, the micro-wind turbine had a mean

estimated output of 1.8 GJ<sub>e</sub>/yr and a 5<sup>th</sup> to 95<sup>th</sup> percentile range of 0.7–3.4 GJ<sub>e</sub>/yr. For eight ‘urban’ locations the mean output estimate was 0.6 GJ<sub>e</sub>/yr while the 5<sup>th</sup> to 95<sup>th</sup> percentile range was 0.2–0.9 GJ<sub>e</sub>/yr. While the solar PV estimates are based upon the combination of a field trial and relatively well-established modelling, the micro-wind estimates were based upon a methodology designed by the author and require further validation. A small recently-completed field trial has provided crude and tentative corroboration of the urban micro-wind estimations, but a larger trial that was due to report imminently at the time of writing will aid more robust validation.

In order to give context to the micro-generator output estimations, another objective of this research was to synthesise and analyse data regarding the use of energy within households (Chapter 4). Comparisons with household electricity demand indicate that the average solar PV output, as represented by mean and modal averages, is equivalent to 27–57% of the (mean or modal) average household electricity usage. While these may be taken as ‘typical’ proportions, the wider range of minimum and maximum solar PV outputs is the equivalent of 21–67% of average annual demands. Similarly, the average (mean or modal) micro-wind turbine output was found to be the equivalent of 5–13% of an average (mean or modal) household’s electricity demand each year, compared to 2–5% for urban wind turbines. Given the minimum and maximum ‘open’ micro-wind outputs, the percentage range increases to 3–31% of average demands, while the minimum and maximum ‘urban’ outputs represent 1–9% of average demands.

It is highly unlikely that all of the electricity generated by the solar PV system or micro-wind turbine will be used by the householder, since in the assumed grid-tied installation electricity will be exported to the grid whenever generation exceeds demand. Literature referred to in this thesis suggests that the percentage of electricity exported will be in the region of 50% for solar PV (with a likely range of 25–70%), while 33–55% could be exported for the micro-wind turbine. These figures will vary with the relationship between generation and demand, and should only be viewed as indicative. There are a range of technical and economic implications of electricity export, but although touched upon in Chapter 7 these were beyond the scope of this research.

The SHW system differs from the micro-wind and solar PV system in that it directly supplies an *energy service* – hot water – to the householder. The electricity micro-generators, in contrast, provide an interim energy carrier that is subsequently employed to provide energy services. These two situations have differing system boundaries – one at entry to the household and one that extends to the energy service. This means, therefore, that direct output comparisons between SHW and the electricity micro-generators are not strictly valid.

Using a performance model based upon field trial measurements, the SHW system has been estimated to provide an energy output of 1.9–3.5 GJ<sub>th</sub> of hot water for appropriate installations across the UK. These outputs represent 28–52% of the assumed household hot-water energy demands, which broadly agree with other literature regarding SHW systems in the UK. The use of this system does not impinge upon the external, established

energy systems in the same way that electricity micro-generators may do, since all hot water is used within the household.

The concept of *exergy* can provide complementary insights to that of *energy*, and so it has been applied within this thesis where pertinent. It was shown that, in contrast to the electricity micro-generators, the exergy output of a SHW system is significantly lower than its energy output. An illustrative example based upon simplistic, annual average values suggests that the exergy output will be approximately 10% of the energy output. While this may at first glance seem like poor performance, it is in fact appropriate since the demand is for low-temperature and hence low-exergy hot water. It is likely that at least some of the electricity provided by the electricity micro-generators will be employed for similar low-quality applications, and hence the use of their output would exhibit 'poor' exergy performance.

Of greater relevance, exergy insights show that the use of SHW reduces the large, *non-renewable*, and mostly unavoidable exergy destruction associated with the use of fossil fuels or electricity to provide low-quality hot water. Such heating processes dominate the energy-use patterns of households. 25% of the fuel or electricity used by an average household is for hot water provision, and more than 80% of total usage is for low-quality heating in general. The fossil-fuel based heating systems typically employed in households have an average energy efficiency of approximately 74%, but an exergy efficiency of only 13% (in 2007), which suggests significant room for thermodynamic improvement. Although a SHW system also suffers a large exergy destruction when converting high-quality solar energy into low-quality hot water, this is less of a concern in the context of dependence on non-renewable fossil fuels and the associated carbon dioxide emissions. When installed alongside a modern gas boiler, oil boiler, or electrical immersion heater, the SHW system is estimated to avoid the use of 2.6–6.4 GJ/yr of delivered fuel and/or electricity.

The energy provided by the micro-generators displaces the use of energy from the established supply systems. Any reduction in fuel or electricity use at the household, as a result of the micro-generator, also represents a reduction of upstream energy use by the associated supply systems. To enable estimates of overall savings, Chapter 2 met the objective of synthesising and describing data regarding the established methods of energy supply in the UK. For each supply system, estimates were made of the *Energy requirement for energy* (ERE) and associated *carbon-emission factors* for the energy carriers they deliver. These indicators communicate how much energy resource is required, or how much carbon dioxide is emitted, per unit of energy delivered to and used by society. They can therefore be used to estimate the overall savings enabled by each unit of energy displaced at the household by a micro-generator. It was found that, on average, 1.2 units of energy resource (in NCV terms) are sequestered for every unit of natural gas delivered to UK households, and that 0.24 kg of CO<sub>2eq</sub> have been emitted (in total) once each kWh of gas has been used within the household. A similar average ERE and carbon-emission factor for oil is 1.4 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.33 kgCO<sub>2eq</sub>/kWh respectively, while for electricity they are 3.1 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.58 kgCO<sub>2eq</sub>/kWh.

The calculation of *average* EREs and carbon-emission factors is relatively simple – total quantities of resource use are divided by total quantities of delivered energy over a time period of, for instance, one year. But micro-generators create a *marginal* reduction in the use of the supply systems. While the simplifying assumption was made that the average value is reasonable in the case of gas or oil, Chapter 2 concluded that marginal values should be used in the case of electricity. This is because of the complexity of electricity generation – only certain *marginal plant* will reduce output in response to localised generation by a micro-generator. A range was estimated for marginal EREs and carbon emissions factors, which were 2.3–2.9 MJ<sub>resource</sub>/MJ<sub>delivered</sub> and 0.49–0.76 kgCO<sub>2eq</sub>/kWh respectively. The upper end of the range represents a marginal plant mix of 50% coal to 50% gas, while the lower end represents a mix of 98% gas and 2% coal, and all values include amortised life-cycle impacts of the supply system components. The difference in values represents an expected increased use of gas in place of coal generation out to the year 2020. While the carbon-emission factors are within the range of other published marginal values, it is recommended that further work investigate the marginal energy and carbon savings enabled by micro-generation in more depth. This should incorporate consideration of the likely non-linear effects of increasing penetrations of micro-generators.

On the basis of EREs and carbon-emission factors outlined above, and excluding the urban micro-wind turbine, the three micro-generators were estimated to enable annual savings of between 1.6 and 21 GJ<sub>NCV</sub> of energy resource (mostly fossil fuels), and between 95 and 1500 kgCO<sub>2eq</sub>. At the upper end of the range of savings is the PV system, which could be expected since it has a large annual output and because electricity is relatively energy and carbon intensive. At the lower end of the range are the savings provided by the the ‘open’ micro-wind turbine given its lowest (5<sup>th</sup> percentile) estimated output. To give the estimated carbon-emission savings context they can be compared to the mean carbon emissions of a UK household, which were 1600 kgCO<sub>2eq</sub>/yr in 2004.

A major reason for interest in micro-generation technologies is their potential to reduce carbon-dioxide emissions and enhance energy security by reducing use of, and dependence upon, fossil fuels. For micro-generators to achieve this, they need save more energy and carbon than that ‘embodied’ within them. This research found that all three micro-generators – even including the ‘urban’ micro-wind turbine – would payback their energy and carbon ‘debts’ within their (varying) lifetimes by displacing the established supply systems. The fastest payback (0.4 years) was achieved by the ‘open’ micro-wind turbine when providing the maximum estimated annual output, closely followed by the best results for the solar hot-water system when installed alongside an electrical immersion heater (0.5 years) or oil-fired boiler (0.8 years). Overall, the open micro-wind turbine was found to pay back within 3.1 years (for all estimated outputs), while the SHW system was found to pay back within 2.5 years for all scenarios considered. Although the solar PV array was seen above to enable the greatest energy-resource and carbon savings, its larger embodied energy and carbon mean it generally has longer payback periods – in the range 2.5–7.4 years. These combined results indicate that all three micro-generators can indeed contribute to a reduction in both the use of fossil fuels and the emission of carbon dioxide.

The net energy and carbon analyses reported here are broadly similar to those of other literature reviewed within this thesis. The evidence-base is still relatively small, particularly regarding micro-generation in the UK, but it is indicating that the all three micro-generator types in general can provide net energy and carbon benefits given appropriate installations. Nevertheless, while the micro-generators assessed here can reduce the use of the established systems they cannot provide a direct substitute for them, at least given current configurations.

Thermodynamic analysis techniques have both advantages and disadvantages. Given the widespread desire for significant changes in the way energy is supplied and used, a key advantage of thermodynamics is its ability to analyse the performance of, and potential for improvement within, energy transfers and transformations. The need for a widely drawn and clearly defined *system boundary*, and the need to account for the whole *life cycle* of the product or service in question, are fundamental to the technique of *energy analysis* (IFIAS 1974). It encourages a system-wide approach that is necessary to enable an overall improvement in the energy system. But though thermodynamics has a role to play in aiding energetic improvements, it is just one of many analysis techniques. Like many other quantitative methods, it reduces a complex system into specific and exclusive quantities of interest, such as *energy* and *exergy*, and will therefore miss many other important factors influencing the operation of the energy system. This indicates that thermodynamics should be applied as one of a range of analysis tools, and hence this research contributed to an interdisciplinary appraisal methodology that involves environmental life cycle assessment and economic cost-benefit analysis. Various aspects of the methodology and its results may be found in Allen et al. (2008a and 2008b). In turn, the integrated appraisal has contributed to a wider research consortium – the EPSRC-led SUPERGEN ‘Highly Distributed Power Systems’ (HDPS) Consortium. The consortium involves researchers and practitioners from a variety of other disciplines, applying techniques such as electrical network modelling, building simulation, and other economic analysis methods. Some recent publications arising from SUPERGEN HDPS were recently brought together in a special issue of the Journal of Power and Energy, published by the UK’s Institution of Mechanical Engineers, to which the reader is guided for further information (see Burt et al. 2008).

### 8.3 MAIN CONTRIBUTIONS OF THIS RESEARCH

A key, over-arching aspect of this research was the integrated, system-wide approach taken during the thermodynamic and carbon analyses of micro-generation technologies, as opposed to exclusive focus upon individual components of the energy system.

In order to provide necessary context for the thermodynamic and carbon analyses of selected micro-generators, the research included the:

- Synthesis and analysis of data regarding the established methods of energy supply to UK households (Chapter 2). This included the determination of the overall energy-resource requirement, and carbon-emissions associated with, units of various residential energy carriers (natural gas, heating oil, and electricity). In the case of electricity, the energy-resource requirement and carbon emissions associated with *marginal* plant were estimated.
- Synthesis and analysis of energy-demand data for the UK's residential sector. This included a thermodynamic (energy and exergy) analysis of energy use within a typical UK household.

In response to the lack of quantitative data regarding micro-generator performance in the UK, the following analyses were carried out:

- Estimation of the energy and exergy outputs of selected micro-generators (particularly for the micro-wind and solar hot-water system).
- Comparison of outputs with typical UK household energy demands.
- Estimation of the overall energy-resource and carbon-emission savings enabled by the micro-generators.
- Estimation of the net energy and carbon performance of the micro-generators. This indicates that all three micro-generators can aid progress toward the UK energy policy goals of reducing carbon emissions and enhancing energy security.

A move toward a more sustainable energy system requires an interdisciplinary assessment and improvement process. This research has therefore contributed to the development and application of an 'integrated appraisal' methodology that includes, alongside thermodynamic analysis, environmental *life cycle assessment* (LCA) and economic *cost-benefit analysis* (CBA). These integrated methods, and their application, have been presented and discussed by Allen et al. (2008a and 2008b).

## 8.4 RECOMMENDATIONS FOR FURTHER WORK

Recommendations for further work have been given at relevant points throughout this thesis. The key points are:

- It is recommended that forthcoming empirical (field-trial) data regarding the performance of micro-wind turbines and SHW systems are used to corroborate or alter the estimations presented in this thesis.
- This research has focused on the *annual* performance of micro-generation technologies. It is recommended that further work investigate performance over shorter timescales, including consideration of the stochastic nature of micro-generator outputs and household energy demands.
- It is recommended that further work investigate the implications of combinations of micro-generation technologies for households or groups of households. For example, the use of micro-wind turbines in conjunction with solar PV arrays and/or solar hot-water systems.
- It is recommended that the methodology developed and described in this thesis is used to analyse the performance of alternative micro-generation and other energy-supply technologies.
- Estimating the energy-resource and carbon savings provided by the micro-generators is non-trivial, because their impacts on the wider energy system are uncertain (particularly in the case of the electricity micro-generators). It is recommended that further work investigate these impacts in more depth, and iterate the energy-resource and carbon-saving estimations for the micro-generators. This should incorporate consideration of the likely non-linear effects of increasing penetrations of micro-generators.
- Micro-generators are a supply-side option for reducing the fossil-fuel use and carbon emissions of the residential sector. There is, however, a large potential for demand reduction through improvements in the way that energy is used within households. Such improvements may influence the appropriate mix of supply technologies. It is therefore recommended that a systematic 'bottom-up' analysis is undertaken in future work. In this way a thorough assessment of the overall improvement potential within the residential sector can be provided, and micro-generation assessments can then form a part of this coherent whole. Sources of information identified during this research are outlined at the end of Appendix B (p.213). This thesis has demonstrated that the concept of *exergy* could be usefully applied, alongside that of *energy*, when carrying out such a study.





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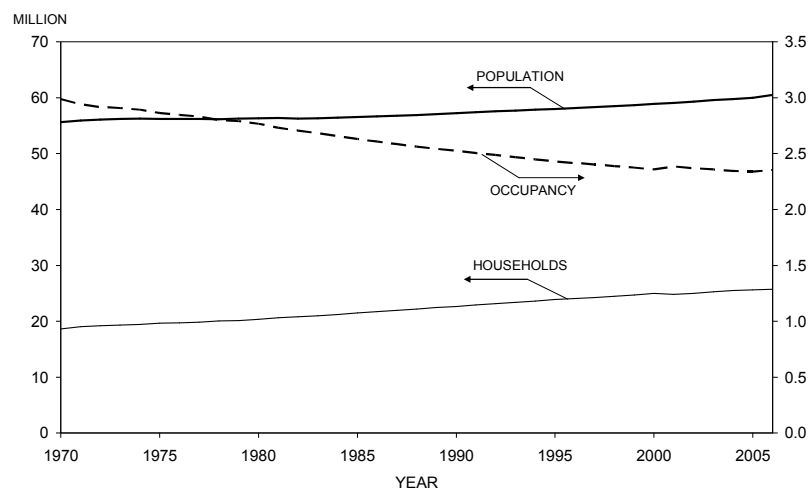


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## APPENDIX A

### THE UK HOUSING STOCK

Figure A-1 shows the number of people and households in the UK, along with the resulting number of people (occupancy) in the average household, during the period 1970–2006. Population and household numbers in the UK have been growing since 1970, by 10% and 29% respectively by 2006, resulting in a trend of decreasing average occupancy. In 2006, household numbers were approximately 25.7 million and the population was 60.5 million, giving an average occupancy of 2.4 people per household.

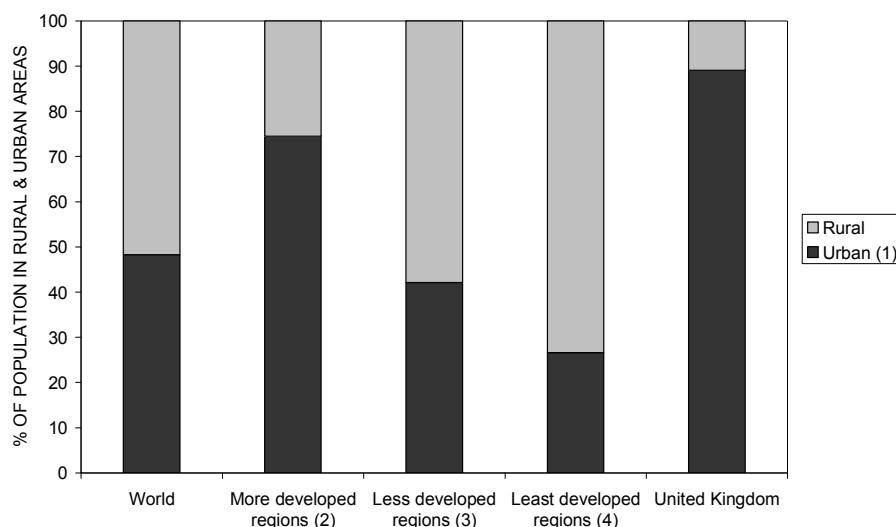


**Figure A-1: Number of households, population, and average household occupancy in the UK, 1970–2006**  
(Source: DTI 2007a)

National housing condition surveys, such as the English Housing Condition Survey (Communities and Local Government 2008), give detailed information about the makeup of the housing stock, on the basis of household surveys. This information can be combined with household energy-related information published by the Building Research Establishment ('BRE'; e.g. Shorrocks and Utley 2003) to give useful data with which to characterise the UK residential sector. Categories used to describe the housing stock include building type (e.g. semi-detached house, terraced house, flat), age, floor area, and construction materials. All can affect household delivered energy use; particularly that used for space heating. However, the focus of this thesis was the assessment of micro-generator performance, and household energy use is contextual information rather than primary research. A detailed breakdown of the housing stock was therefore beyond the scope of this thesis, and a simpler 'average UK household' was considered instead. Further work could consider a more detailed breakdown of the housing stock in order to investigate the types of household for which different micro-generation technologies would be most appropriate. A useful input for such work could be a recent synthesis of housing stock information that was produced as an internal working document by partners

in the SUPERGEN HDPS consortium (Beyer and Kelly 2006), for use within the building modelling section of the consortium.

Figure A-2 show the proportions of populations around the world living in rural and urban areas in 2003, produced by the U.N.'s Department of Economic and Social Affairs (U.N. 2003). It indicates that as a country develops, populations tend to become more urbanised. Approximately 90% of the population in the UK live in urban areas – considerably higher than the global average – and the U.N. estimates that this proportion will see a modest rise to 92% by 2030.



**Figure A-2: Proportions of national populations in urban areas (Source: U.N. 2003)**

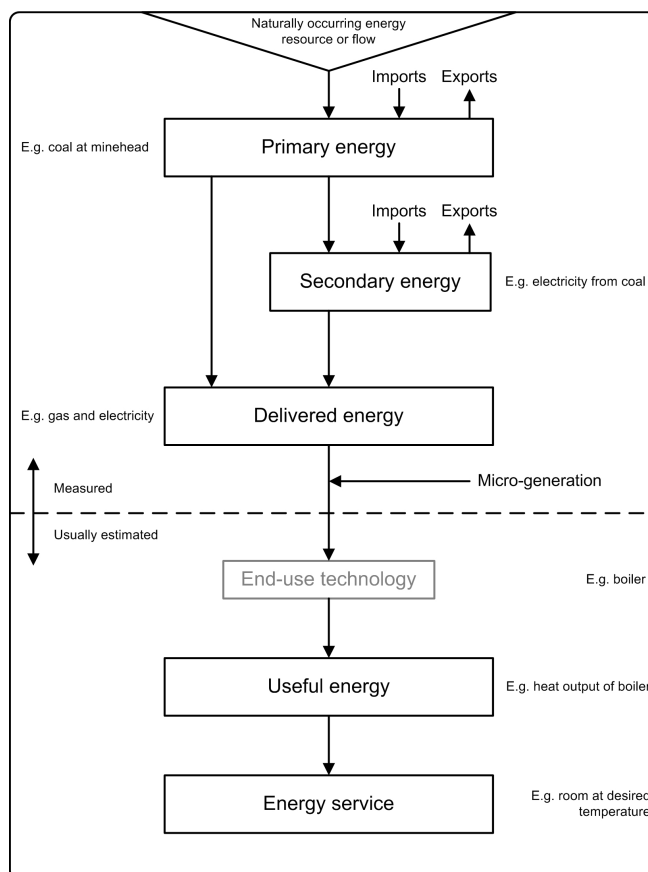
**Figure Notes**

1. Urban agglomerations are those of 1 million inhabitants or more in 2003. An agglomeration contains the population within the contours of contiguous territory inhabited at urban levels of residential density without regard to administrative boundaries.
2. 'More developed regions' comprise Europe, Northern America, Australia/New Zealand and Japan.
3. 'Less developed regions' comprise all regions of Africa, Asia (except Japan), Latin America and the Caribbean plus Melanesia, Micronesia and Polynesia.
4. The 'least developed regions', as defined by the United Nations General Assembly in 2001, included 49 countries, of which 34 are in Africa, 9 in Asia, 1 in Latin America and the Caribbean, and 5 in Oceania.

## APPENDIX B

# TERMINOLOGY FOR DESCRIBING ENERGY USE

The end-user of energy wants a particular *energy service*: a room at a desired temperature; transportation over a certain distance; the manufacture of a product from raw materials; and so on. The energy flows enabling the provision of such energy services may be traced all the way back to their natural forms, and in doing so they are commonly quantified and discussed at the variety of stages shown in Figure B-2. Haldi and Favrat (2006) highlight that there are inevitable losses along the way in both quantity (e.g. heat losses during electricity generation) and quality (e.g. the use of fuels or electricity to provide heat at low temperature).



**Figure B-2: Terminology for describing energy use**  
Adapted from Haldi and Favrat (2006) and BERR (2008a)

In their natural forms, energy sources are either stored fuels or ambient flows, as discussed in further detail in Appendix C. At the point of extraction from fuel reserves or ambient flows, the UK's national energy statistics (BERR 2008a p.201) define energy forms as *primary energy*, as shown in Figure B-2. This is a common, but often inconsistent, definition. Partly because of its inconsistent definition, but also for other reasons now

outlined, primary energy is a somewhat controversial term, and while it is commonly used it is best regarded with care (Spreng 1988; Patterson 2007b).

For fuels, 'primary energy' refers to the marketable quantity extracted from the reserve (BERR 2008a p.207), such as the crude oil at the wellhead or the coal at the mine-mouth. Any resource lost during the extraction process is thus excluded from the account, as is commonly the case (Slessor 1978; Spreng 1988). When primary fuels emanate from within the geographical boundary covered by the statistics, the energy requirement of extracting such resources is directly or indirectly included in the statistics. Direct energy requirements will be counted under categories such as 'energy industry use', while indirect energy requirements for extraction machinery and so on will have been included in previous years' statistics (as long as they were manufactured in the country in question), for example as industrial (manufacturing) energy use.

The treatment of imports in BERR (2008a) invalidates the definition of primary energy as that 'drawn (extracted or captured) from natural reserves or flows'. Rather than being accounted for in their true primary (natural) forms, they are delivered forms of energy entering the economy, and they have an upstream transportation energy-use and in some cases processing energy requirements (e.g. in the case of imported petroleum). These transportation and any processing requirements should have been included in the national energy statistics of their countries of origin, though these are neither certain nor easily traced.

'Primary electricity' is referred to by BERR (2008a) as that coming from ambient renewable sources (wind, solar, hydro) as well as nuclear-derived and imported electricity. They are regarded as 'primary' because there are currently no other uses of the energy resource upstream of the generation (BERR 2008a p.207). In the case of ambient renewables, the 'primary energy' entered in the UK's national statistics is the electricity actually provided; their operational energy source (e.g. solar irradiation) is not included. This fits with the definition of 'extracted from natural flows'. In the case of nuclear electricity the nuclear fuel input (the 'primary energy' input) is accounted for in terms of the enthalpy increase of the working fluid caused by nuclear fission. This is somewhat controversial, for example because it ignores the burn-up ratio that indicates how much heat is produced from a given amount of nuclear fuel (Spreng 1988 p.76).

After conversion from physical quantities (e.g. tonnes of coal or cubic metres of natural gas) into energy units such as joules, primary energy quantities are often aggregated or compared. This can be an oversimplification since it may imply substitutability that does not exist, and, for fuels, care must be taken with 'gross' or 'net' calorific values. A joule of oil is different in many ways to a joule of electricity or a joule of hot water, for example in terms of its capacity to do useful work, cost, cleanliness, and technical requirements for use.

*Secondary or intermediate energy* (BERR 2008a, Haldrup and Favrat 2006) is that derived from primary energy forms, such as petroleum from crude oil or electricity from coal.

Similar issues arise when counting secondary energy flows in simple energy units as those discussed for primary energy quantities. Conversion losses from primary to secondary energy forms are significant in the case of electricity generation from fuels; they amounted to approximately 62% of the primary energy entering UK power stations in 2007 (BERR 2008f).

*Delivered energy* refers to commercial energy carriers (e.g. fuel or electricity) delivered to the end-user, and such statistics are largely derived from commercial energy sales information (Spreng 1988). Electricity and (sometimes) district heat are the only forms of delivered energy that are sold by the unit of energy. Fuels tend to be sold by volume or weight, which are again often converted into energy units to enable comparison or aggregation. It is important to note that delivered energy refers to *commercial* forms of energy only. Non-commercial energy forms, such as solar irradiation and non-commercial wood fuels, are not directly included in delivered energy accounts. The substitution of such energy forms for commercial delivered energy will be reflected in most energy statistics only indirectly, by a reduction in the use of the latter.

*Useful energy* is the amount of energy reaching the final user after conversion in an *end-use technology*. Spreng (1988) points out the subtle but important distinction between this quantity and the concept of *energy services* (defined below), and gives the example of passenger transport. The energy service is the passenger-miles travelled; this is the quantity of interest to the passenger and the ideal basis for accounting. The useful energy required to enable this transportation, however, can vary for a specified passenger-distance. For example, if the passenger travels by bus, uphill and against a headwind, a greater quantity of useful energy will be required from the engine than if the journey is downhill with a tailwind. In addition to this accounting difficulty, the point of measurement of useful energy is somewhat arbitrary (e.g. should losses in wheels and tyres be included, or is it just measured at the engine output?). Similarly, and particularly relevant to this thesis, heating can be efficient because a boiler has a high conversion efficiency of fuel to heat generated, or because the building is well insulated and requires little heat input. The concept of useful energy generally applies to the former of these two, and is again arbitrarily defined: it is usually the heat output of the boiler, but it could instead, for example, be the heat input to the radiators after plumbing losses.

Calculating energy demands on the basis of *energy services* is thus the most complete and hence ideal method of accounting for and analysing energy flows. They account for what is actually desired by the end-user and they will therefore, for example, enable the investigation of *all* potential improvements, such as better insulation or alternative lighting methods, alongside supply-side improvements. The method of accounting for space heating, for example, would ideally be some measure like heated volume multiplied by heating degree days (Spreng 1988), rather than the delivered energy (e.g. gas) used by a boiler or the useful energy (as hot water output) obtained from that boiler. Such statistics are not generally compiled, however, in national and international energy statistics – a disadvantage that weighs against the advantage of the latter’s detailed and broad coverage. Sources of information and guidance identified during this research that could contribute

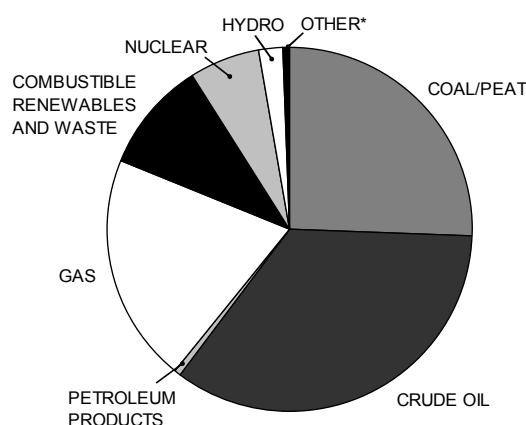
to an up-to-date 'bottom-up' analysis include Leach et al. (1979); Goldemberg et al. (1988); the BRE's 'BREDEM' and 'BREHOMES' models (e.g. Shorrocks and Dunster 1997); Oxford University's 'UK Domestic Carbon Model' (e.g. Palmer et al. 2007); and DEFRA's Market Transformation Programme (e.g. Market Transformation Programme 2008).

## APPENDIX C

### ENERGY SOURCES AND SOME IMPLICATIONS

Naturally available forms of energy may be classified as either as *fuels* or *ambient flows*. Etymologically, a fuel is ‘material for a fireplace’ – it is matter that is burnt to produce heat (Patterson 2007b). *Fossil fuels* are fossilised biomass that were formed over millennia (McKendry 2002), and *biomass fuels* are those derived more directly from photosynthesis and the sun’s daily flux. Biomass fuels have been utilised ever since humans began to use fire but, since their discovery and the inventions enabling their increased use, fossil fuels have become the dominant fuel in many countries. Since the middle of the 20<sup>th</sup> century, the term *nuclear fuels* has been used to refer to ores containing heavy elements such as uranium and thorium because, similar to the use of fossil and biomass fuels via combustion, nuclear fission is used to provide heat. Nuclear fuels have played a role in human energy systems since the 1950s (Hammond and Waldron 2008).

The world’s societies depend heavily upon fuels as a source of energy, both historically and today. They are a convenient stored form of energy; highly concentrated in the case of fossil and nuclear fuels particularly, and they may be traded, transported, and used when and where they are desired. Fuels constituted 98% of the global primary energy use accounted for by international energy statistics in 1973, and 97% in 2006, the latter shown in Figure C-1 (IEA 2008). The distribution and availability of fuels – particularly of fossil and nuclear fuels – is uneven around the world, which has significant implications for the energy security of many nations.



**Figure C-1: Global primary energy use in 2006** (Source: IEA 2008)

\* ‘Other’ includes geothermal, solar, wind etc.

*Ambient energy flows*, in contrast to fuels, are in constant flux and are neither traded nor transported<sup>13</sup>, so they are available only locally and, in general, variably. Examples include solar, wind, wave, tidal, natural-flow hydro, and geothermal energy flows. Such energy

<sup>13</sup> Though their derivatives, such as electricity, are often traded and transported.



sources comprised a minor form of primary energy input in 2006, as shown by the 'other' category of Figure C-1.

The distinctions between fuels and ambient energy flows have significant implications for their modes of use and associated supply-chains, which in turn affects their reliability and cost. The supply-chains for each fuel-type are typically long and complex, for industrialised countries at least, and hence they require substantial infrastructures. To give one example, crude oil, once found, requires extraction, processing and transportation, the latter often over large distances (Slessor 1978). Technologies that convert fuels either directly into heat (e.g. for household heating or within an engine providing transportation) or into a derivative energy carrier (e.g. electricity) are convenient because they can be called upon when desired, but they of course rely upon a sufficient supply of that fuel. An ongoing fuel cost can be a considerable part of the overall costs of such technologies, and fuel prices can vary significantly (see, for example, the recent variations in the prices of crude oil, petroleum products, and natural gas in IEA 2008). Ambient energy conversion technologies, in contrast, depend upon locally available energy sources and hence have the advantage of being independent of fuel-related supply chains<sup>14</sup>, but usually also have the disadvantage of being based upon variable-flow sources. The majority of their economic cost comprises capital and possibly maintenance costs that are, at present, often relatively high, but of course they have no fuel cost.

A further distinction between energy sources concerns their depletion (or lack of). Fossil and nuclear fuels are *non-renewable* resources because they are being depleted with their use (they are not renewed within the timescale in which humans are using them). Biomass fuels and ambient energy flows, in contrast, are *renewable* because they are continually, if variably, available. Haldi and Favrat (2006) highlight that a consequence of these characteristics is a differing method of quantification for non-renewable and renewable energy sources. Non-renewable energy is accounted for in stored energy quantities (e.g. J/kg or J/m<sup>3</sup>) whereas renewable sources are often referred to in terms of energy flux (e.g. J/m<sup>2</sup>/yr).

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<sup>14</sup> In the case of electricity derived from ambient sources, however, supply chains can still be expansive.

## APPENDIX D

# AGGREGATION AND ENERGY QUALITY

The problem of accounting for quality differences when aggregating energy flows was discussed in Section 2.3.7.6 (p.22). The methods of aggregation outlined at that point involved either *enthalpy* (energy) or *exergy*, the latter of which accounts for *thermodynamic* quality differences. Two other approaches – *emergy* and economics-derived methods, were mentioned but not discussed. They are briefly outlined here together with the reason for their exclusion from this research.

Howard T. Odum was one of the first scientists to recognise the need to distinguish between energy vectors of different qualities (Hammond 2007a). Among his contributions to the energy analysis and related literature<sup>15</sup> was the concept of *emergy*, an alternative to *exergy*, to account for differences in quality. This concept measures, values, and aggregates energy of different forms by their *transformities*; the amount of embodied energy (measured in *solar emjoules*) used to produce another type of energy in thermal equivalents (Cleveland et al. 2000; Hammond 2007a). These transformities reflect an energy hierarchy in terms of quality, and Brown and Ulgiati (2004) suggest that transformations can be arranged in an ordered sequence: a joule of solar energy is required to create a joule of organic matter via photosynthesis; many joules of organic material were required to produce a joule of fossil fuel over geological timescales; several joules of fossil fuel are needed to generate a joule of electricity, and so on (Hammond 2007a). Thus, fuels with high transformities are considered to be more economically useful. Emergy, however, may only partially reflect energy quality (Hammond 2007a). Indeed Cleveland et al. contend that the methodology may be inconsistent with its own basic tenant, namely that quality varies with embodied energy. Coal deposits, for example, were laid down over a wide variety of geological periods and thus have vastly different embodied emergies, yet only a single transformity for coal is normally used. Furthermore, the methodology depends upon plausible but arbitrary choices of conversion technology and hence conversion efficiencies, for example the conversion of coal into electricity (Cleveland et al. 2000). Finally, and perhaps most significantly, the emergy method requires detailed calculations using data from a variety of sources; the quality and uncertainty of which is unclear to the external user or reviewer (Hammond 2007a). The methodology was thus considered inappropriate, in its current form, for application within this research and thesis, although further work could investigate the concept further.

Both the *exergy* and *emergy* based interpretations of ‘quality’ have a notable disadvantage: they are one-dimensional, recognising only either thermodynamic quality or

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<sup>15</sup> Odum’s early contribution of a biophysically-based, systems-oriented model of the relationship between society and the environment, and the publication of his book ‘Environment, Power, and Society in 1971 (Odum 1971) helped to lay the foundations for the biophysical analysis of energy and material flows (see, for example, Cleveland et al. 2000 and the review by Hammond 2007a).

transformity. In reality there are many other attributes that distinguish different energy forms, such as physical scarcity, energy density (e.g. J/kg), cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so on (Cleveland et al. 2000). From a societal or economic perspective, therefore, exergy or emergy provide incomplete measures of quality. In economics the value of an energy carrier is determined by its price, which in turn is influenced by a complex set of attributes such as those just listed. Where the question being asked requires the aggregation of energy flows within economic systems – i.e. the relationship between energy and the economy – Cleveland et al. (2000) argue that an economic approach such as Divisa aggregation or a direct measure of marginal product are more appropriate than one-dimensional physical measures such as exergy and emergy. The focus of this research, however, was upon physical quantities of energy rather than the economic utility of energy flows, and hence the physical measures of energy and exergy were used in this research. Further work certainly could, however, investigate different methods of energy aggregation in the context of the micro-generators assessed here.

## APPENDIX E

### PUBLISHED PAPERS

The following three papers are reproduced in this Appendix:

- pp.222–235** Allen, S. R., Hammond, G. P., Harajli, H. A., Jones, C. I., McManus, M. C., & Winnett, A. B. 2008a. "Integrated appraisal of micro-generators: methods and applications", *Proc.Instn Civil Engrs: Energy*, vol. **161**, no. 2, pp. 73-86. This paper is a revised and extended version of work originally presented at the '1st International Conference on Micro-Cogeneration Technologies and Applications' (Micro-Cogen 2008), Ottawa, Canada, 29 April - 1 May 2008, Paper MG2008-SG-005, 8pp.
- pp.236–251** Allen, S. R., Hammond, G. P., & McManus, M. C. 2008b. "Energy analysis and environmental life cycle assessment of a micro-wind turbine", *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. **222**, no. 7, pp. 669-684.
- pp.252–268** Allen, S. R., Hammond, G. P., & McManus, M. C. 2008c. "Prospects for and barriers to domestic micro-generation: A United Kingdom perspective", *Applied Energy*, vol. **85**, no. 6, pp. 528-544. This paper is a revised and extended version of work originally presented by the present author at the '3rd International Green Energy Conference' (IGEC-III), Mälardalen University, Västerås, Sweden, 18-20 June 2007, pp. 1284-1295.

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## Integrated appraisal of micro-generators: methods and applications

S. R. Allen, G. P. Hammond, H. A. Harajli, C. I. Jones, M. C. McManus and A. B. Winnett

**A range of integrated appraisal techniques have been utilised to study the comparative performance of various domestic micro-generators that have been proposed as possible decentralised energy resources for 'low carbon' buildings. Energy, environmental impact and cost-benefit analysis methods, employed on a 'whole systems' basis, are described. The application of this 'toolkit' is illustrated by way of the evaluation of three micro-generators: a micro-wind turbine; a (generic) solar photovoltaic array; and a solar hot water system. It is estimated that all three generators, in appropriately sited installations, have energy and carbon paybacks well within their lifetimes. Significant life-cycle environmental impacts are associated with the use of aluminium to fabricate both the solar hot water unit and the micro-wind turbine. All three domestic micro-generators were found to be economically unattractive in the present liberalised British energy markets from a societal perspective. Increased production volumes and technical innovations in the next generation of devices, such as improvements in their manufacturing processes and operational efficiencies, are necessary in order to render micro-generators economic propositions. However, there are likely to be many external and unpredictable changes to the global energy market during the years to 2050. These could dramatically alter the prospects for distributed generation.**

### 1. INTRODUCTION

The domestic building sector, which constitutes around 30% of the UK's final energy demand and about 23% of greenhouse gas (GHG) emissions, can play an important role in carbon dioxide (CO<sub>2</sub>) abatement. An uptake of low- or zero-carbon (LZC) distributed energy resources (DERs), sometimes referred to as micro-generators, would help this sector to reduce fossil fuel energy use and carbon dioxide emissions. However, energy efficiency and demand reduction measures<sup>1,2</sup> should be adopted before embarking on the installation of such micro-generators. For example, householders could save energy by the adoption of higher levels of thermal insulation (including draughtproofing, external cladding or double glazing), low-energy consumption patterns (energy-efficient appliances, low-energy light bulbs, and by turning electronics off and avoiding standby), and better control of central heating systems. Once implemented these low-energy load profiles should be used to determine the potential role for DERs.

'Decentralised', or 'distributed', energy supply refers to a wide range of technologies that do not rely on the high-voltage transmission network or the gas grid, including the generation of energy close to the point of use.<sup>3</sup> It can denote a range of generator sizes—from district or community level down to individual households. 'Micro-generation' is defined in section 82 of the UK's Energy Act (2004) as the production of electricity or heat from a low-carbon source, at capacities no more than 50 kW<sub>e</sub> or 45 kW<sub>th</sub>. The term embraces a variety of technology options, including micro-wind turbines, solar photovoltaic (PV) arrays, solar hot water (SHW) systems, micro-combined heat and power (CHP) units and heat pumps. Some of these technologies are based on renewable resources (which are essentially 'zero carbon'), while some increase the energy efficiency of fossil fuel use (and are consequently 'low-carbon' options). For example, current fossil-fuelled micro-CHP plants supply both useful heat and electricity, and in doing so offer the potential for high overall energy efficiencies compared with separate, conventional supply. The Energy Saving Trust (EST) suggested that micro-generators could meet 30–40% of the UK's electricity requirements by 2050.<sup>4</sup>

The notion of integrated appraisal and whole systems thinking is open to a variety of interpretations. Here it is viewed as a mechanism and toolkit for illustrating the interconnections within the energy system, and for identifying significant constraints associated with the adoption of particular technological innovations for the home and associated electricity system. They are viewed as being 'integrated' in the sense that they are interconnected, but yield differing perspectives within a 'sustainability framework' (see Hammond and Winnett<sup>5</sup>). It helps to provide a performance 'snapshot' in time, based on quantitative evaluations. The approach, employed on a life-cycle (or 'full fuel cycle') basis, is illustrated here by reference to a number of selected DERs in the UK context: a micro-wind turbine, a solar PV array and an SHW system. Thermodynamic, environmental and cost-benefit evaluation techniques are described (after Hammond and Winnett<sup>5</sup>) and then applied to the selected micro-generators.

### 2. APPRAISAL METHODS

#### 2.1. Energy analysis

To determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This idea is based on the First Law of Thermodynamics—that is, the

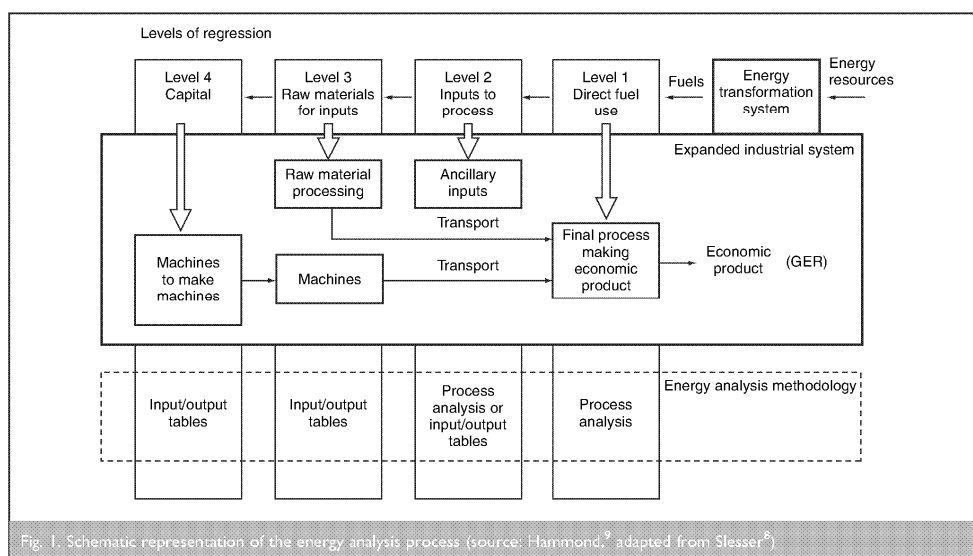


Fig. 1. Schematic representation of the energy analysis process (source: Hammond,<sup>2</sup> adapted from Slesser<sup>8</sup>)

principle of conservation of energy, or the notion of an energy balance applied to the system.<sup>6</sup> It leads to the technique of First Law or 'energy' analysis, sometimes termed 'fossil fuel accounting', which was developed in the 1970s in the aftermath of the oil crisis (see, for example, Roberts<sup>7</sup> or Slesser<sup>8</sup>). Analysis is performed over the entire life cycle of the product or activity, 'from cradle to grave'. It yields the whole-life or 'gross' energy requirement (GER) of the product or service.

The system boundary in energy analysis (EA) should strictly encompass the energy resource in the ground (e.g. oil in the well or coal at the mine), although this is often taken as the national boundary in practice. Thus, the sum of all the outputs from this system multiplied by their individual energy requirements must be equal to the sum of inputs multiplied by their individual requirements. The process consequently implies the identification of feedback loops, such as the indirect, or 'embodied', energy requirements for materials and capital inputs. This procedure is indicated schematically in Fig. 1.<sup>8,9</sup> Different 'levels of regression' may be employed,<sup>8</sup> depending on the extent to which feedback loops are accounted for, or the degree of accuracy desired. The procedure leads to an estimate of the GER, sometimes loosely termed the primary 'energy cost'. It can be used to determine the least energy-intensive industrial processes and materials from a number of alternative options.

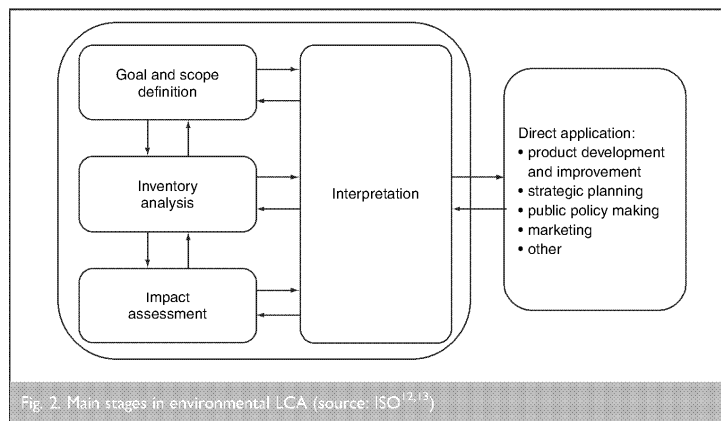
There are several different methods of EA, the principal ones being statistical analysis, input-output table analysis and process analysis (see, for example, Roberts<sup>7</sup> or Slesser<sup>8</sup>). The first method is limited by the available statistical data for the whole economy or a particular industry, as well as the level of disaggregation of the data. Statistical analysis often provides a reasonable estimate of the primary energy cost of products classified by industry. However, it cannot account for indirect energy requirements or distinguish between the different outputs from the same industry.<sup>7</sup> The technique of input-output

table analysis, originally developed by economists, can also be utilised to determine indirect energy inputs and thereby to provide a much better estimate of the GER. This approach is constrained only by the level of disaggregation that is available in national input-output tables. Process EA is the most detailed of the methods, and is usually applied to a particular process or industry. It requires process flow-charting using conventions originally adopted by the International Federation of Institutes of Advanced Studies in 1974–1975.<sup>7,8</sup> The application domains of these various methods overlap (see Fig. 1), and a combination of methods is often adopted.

## 2.2. Environmental life-cycle assessment

It is now widely recognised that to evaluate the environmental consequences of a product or activity, the impact resulting from each stage of its life cycle must be considered. This has led to the development of a range of analytical techniques that now come under the 'umbrella' of environmental life cycle assessment (LCA). Along with other environmental management tools, LCA is becoming more widely adopted in the context of national and international environmental regulations, such as those associated with eco-labelling. In a full LCA study, the energy and materials used, and pollutants or wastes released into the environment as a consequence of a product or activity are quantified over the whole life cycle—again 'from cradle-to-grave'.<sup>10,11</sup>

The methodology of LCA follows closely that developed for EA,<sup>11</sup> especially that of process analysis, but it evaluates a wider range of environmental burdens associated with a product or process over its whole life cycle. This requires the determination of a balance or budget for the raw materials and pollutant emissions (outputs) emanating from the system. Energy is treated concurrently, thereby obviating the need for a separate inventory of embodied energy. LCA is a product- or system-based form of environmental auditing which is often



geographically diverse; that is, the material inputs to a product may be drawn from any continent or geo-political region of the world. Owing to an early lack of consensus regarding methodology, LCA was codified under the auspices of the Society of Environmental Toxicology and Chemistry (SETAC) at a series of workshops in the early 1990s.<sup>11</sup> These largely defined the standard framework for LCA, which subsequently formed the basis of the ISO 14040 series of LCA standards. These were modified, and reduced from four to two standards, in 2006.<sup>12,13</sup>

There are four main stages in the LCA process: 'goal and scope definition', 'inventory analysis', 'impact assessment' and 'interpretation'. These are described as follows and illustrated in Fig. 2. Goal definition is the stage in which the scope of the project is outlined. The inventory analysis is the stage where the bulk of the data collection and analysis is performed. Impact assessment is where the actual effects on the chosen environmental burdens are assessed. This stage is further subdivided into three (or four) elements: classification, characterisation, (normalisation) and valuation. Classification is where the data in the inventory are assigned to the environmental impact categories (GHG emissions, ozone depletion, acidification and the like). In each class there will be several different emission types, all of which will have differing effects in terms of the impact category in question (e.g. GHGs and their differing global warming potentials (GWPs)). A characterisation step is therefore undertaken to enable these emissions to be directly compared and added together. This step yields a list of environmental impact categories for which a single number can be allocated. These impact categories are very difficult to compare directly, and so the current data were normalised with respect to European emissions. This allows a comparison of the importance of each category to be made without attributing subjective valuation. Interpretation or improvement assessment is the final phase of an LCA in which areas for potential improvement are identified and implemented.

The LCA software package *SimaPro* (version 7.1) was used for the present study (following Allen *et al.*<sup>14</sup>). It is a commercial package developed from that originally reported by Heijungs *et al.*<sup>10</sup> at the Institute of Environmental Sciences (CML), Leiden University, the Netherlands. This software enables the

manipulation and examination of inventory data in accordance with the ISO LCA Standards.

### 2.3. Environmental cost-benefit analysis

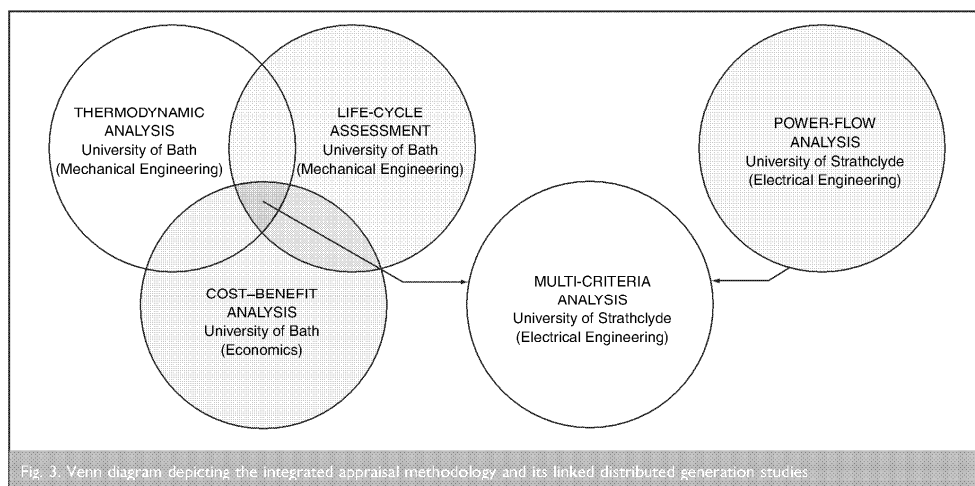
The idea that prices reflect economic value led to the development of the techniques of cost-benefit analysis (CBA) for the assessment of public works projects.<sup>15</sup> They now provide an important input into the evaluation of many projects that have significant impacts on the environment. In such cases it is necessary to internalise some of the costs and benefits that might

otherwise be viewed as being external to the market. This valuation process is uncertain and potentially controversial, often relying on the determination of shadow prices.<sup>5</sup> In mainstream environmental economics, time is routinely dealt with by discounting. The costs and benefits in monetary terms are progressively discounted for future years to allow for the 'time value of money'. This is a source of much criticism from environmentalists, for practical and ethical reasons (see, for example, Broome<sup>16</sup>). Ultimately, the application of CBA results in the determination of a single decision criterion, typically the net present value (NPV) over the project life, the corresponding discounted cost-benefit ratio, or some related parameter. In dealing with risk, standard environmental economics generally assumes a world of calculable probabilities. Thus, a probability distribution for the decision criterion, such as the discounted cost-benefit ratio, is obtained if uncertainty is explicitly taken into account.<sup>5</sup>

Discounted CBA techniques do not adequately reflect the resource depletion problem, at least as long as resource prices reflect mainly short-term trends.<sup>5</sup> Nonetheless, the evaluation of social and environmental costs is obviously useful in identifying where the market has failed to internalise them. This provides governments with an indication of those areas in which action needs to be taken by way of the introduction of economic instruments (such as 'green' taxes and emissions permits) that can offset market deficiencies.

### 2.4. Other approaches

Energy analysis as described above takes no account of the 'quality' of the energy source in a thermodynamic sense. Electricity, for example, may be regarded as an energy carrier having a high quality, or exergy, because it is readily converted into work. In contrast, low-temperature hot water, although also an energy carrier, can only be used for heating purposes. 'Exergy' is a property that stems from both the First and Second Laws of Thermodynamics.<sup>6</sup> The distinction between energy and exergy is very important when considering the adoption of different types of electricity generation stations, including CHP plant. Thus, Hammond<sup>6</sup> has argued that it is preferable to employ 'exergy' analysis alongside a traditional First Law EA to illuminate these issues. This was, however, beyond the scope of the present study.



Some of the more ardent advocates of CBA techniques for evaluating new projects with significant environmental impacts imply that they can be used as the sole method of assessment (see the discussion by Hammond and Winnett<sup>5</sup>). There are a number of reasons for discouraging such an approach. First, the various methods for valuing external costs and benefits are all open to criticism.<sup>17,18</sup> The second, and arguably more important, reason for discouraging the sole use of CBA techniques is that they obscure rather than highlight the range of impacts that may emanate from a given project. Decision-makers are typically presented with a single, aggregate decision criterion (such as the discounted cost-benefit ratio), which actually hides many disparate environmental impacts. It is vitally important that the implications of these impacts are faced, particularly by politicians, rather than obscured by the methodology.<sup>5,17,18</sup> Similar remarks apply to other techniques, including 'multi-criteria decision analysis' (MCDA), which also aggregate various distinct impacts of the technological options.

There are several other factors, beyond those discussed above, that should also be considered when assessing the broader energy system. These include electricity network design and operation issues, geographical suitability, planning permission requirements and so on. The integrated appraisal methodology utilised here should therefore be seen as part of a wider interdisciplinary assessment process. Indeed the present findings on the performance of individual micro-generators are being used in the context of a wider planning framework for highly distributed power systems (HDPS) that contain a diverse and significant proportion of DERs. Electrical engineering colleagues at the University of Strathclyde (see, for example, Alarcon-Rodriguez *et al.*<sup>19</sup>) have employed what they describe as 'multi-criteria analysis, or more specifically multi-objective planning' to analyse several conflicting HDPS design objectives within defined constraints and a dynamically changing situation. The multi-objective planning approach has been used with the aid of both network 'power-flow analysis' and inputs from the type of studies reported here. The loose coupling of these methods is illustrated in Fig. 3. Power-flow analysis takes on an added

significance with a high penetration of small, grid-tied residential micro-generators interacting with wider-scale electricity distribution networks.

### 3. COMPARATIVE ASSESSMENT OF THE MICRO-GENERATORS

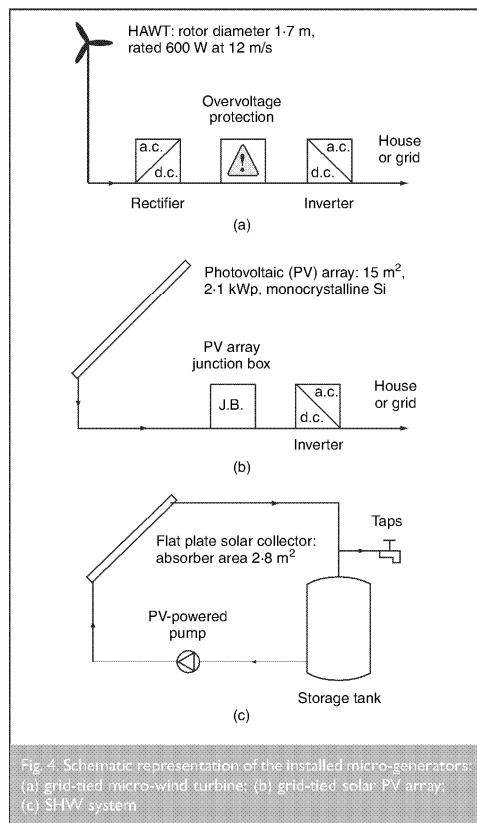
#### 3.1. The selected micro-generators

The methods of energy (EA), environmental impact (LCA) and economic (CBA) assessment described above were applied to three micro-generator technologies, all commercially available in the UK: a micro-wind turbine, a solar PV array, and an SHW system. The grid-tied micro-wind turbine was a horizontal-axis design with a rotor diameter of 1.7 m and a power rating of 600 W at 12 m/s (it is described more fully by Allen *et al.*<sup>14</sup>). The assumed lifetime was 15 years. The turbine has a range of installation options, including free-standing mast or building-mounted. The grid-tied solar PV array was a generic 15 m<sup>2</sup>, 2.1 kWp, monocrystalline system. The SHW system considered comprised a freeze-tolerant flat plate collector, with absorber area 2.8 m<sup>2</sup>, which connects directly to a domestic hot water storage cylinder. Water is circulated by a small pump that is powered by a PV module. The assumed lifetime for both solar systems was 25 years. The three systems, in their installed configurations, are shown schematically in Fig. 4. It is important to note that, in the case of micro-wind and SHW, there are a range of technologies in the marketplace that are likely to perform differently to the specific, commercially available generators studied. The generators considered here are not, therefore, necessarily representative of each type of technology.

#### 3.2. Energy analysis of the micro-generators in use

The micro-generators considered here provide energy carried in the form of electricity or hot water. The differences in thermodynamic quality between electricity and hot water, as discussed above, should ideally be considered alongside the energy (output) quantities presented below. The output estimates are energy supplied to the point of use. This is the electrical socket and the taps, for electricity and hot water respectively.





The electricity output of the micro-wind turbine was estimated through combination of the turbine's published power curve, grid-tie inverter characteristics and a dataset of measured hourly-average wind speeds from across the UK (totalling 2.3 million hours between 1990 and 2006). For 18 'open' sites (i.e. well exposed, most rural terrain), the analysed installation was mast mounted, away from the household. In the case of eight 'urban' sites the represented installation was building-mounted. The estimated annual electricity outputs had a mean value of 870 kWh (range: 280–1500 kWh) for the 'open' environments, which corresponds to a capacity factor (CF, the energy supplied during a given period divided by the energy that would have been supplied had the wind turbine been running continually at the rated power) of 15% (range: 5–29%). In the case of the 'urban' environments the mean value was 160 kWh (range: 60–310 kWh); a CF of 3% (range: 1–6%) (see again Allen *et al.*<sup>14</sup> for further details). The 'urban' estimates are very low compared with the average use discussed below, and consequently only 'open' wind turbines were considered for the remainder of this study. The annual electricity output of the solar PV array was estimated as 1300–2000 kWh (619–952 kWh/kWp), with a UK mean of 1720 kWh (819 kWh/kWp). These values are based on Suri *et al.*<sup>20</sup> and those obtained from the DTL.<sup>21</sup> The energy supplied by the SHW system was estimated for a range of UK sites, using a combination of measured performance data (DTI<sup>22</sup>)

	Energy supplied: kWh		
	Min.	Selected	Max.
'Open' micro-wind (1.7 m rotor diameter, 600 W at 12 m/s)	280	870	1500
Solar PV (15 m <sup>2</sup> , 2.1 kWp monocrystalline)	1300	1720	2000
SHW system (2.8 m <sup>2</sup> , flat plate collector)	650	815	980

Table 1. Energy supplied by micro-generators to the point of use (estimated)

and characteristic monthly solar irradiation quantities (Suri *et al.*<sup>20</sup>). It was assumed that the installation was unshaded and SE–SW facing, with a pitch angle of 15–50°. Distribution losses (between the hot water tank and the taps) are assumed to be 15% of the energy leaving the tank, in accordance with the estimates made by BRE.<sup>23</sup> The annual hot water output of the system is estimated as 650–980 kWh. In such a case, top-up heating is required year-round to satisfy total monthly demand.

A summary of the energy output estimates, with the selected indicative values highlighted, is given in Table 1. The selected values are used in the economic analysis, and to produce the avoided impacts owing to operation in the LCA studies reported below. All micro-generators considered here have variable outputs in the time domain, as they are dependent on the solar and wind resources available in the UK. In the case of micro-wind and solar PV, a grid-tied installation has been assumed, and therefore, if unused by the household, the electricity could be exported to the local network. In environmental terms, as considered here, this would not have a significant effect, assuming localised use. In technical and financial terms, however, export issues will have important implications, although these were beyond the scope of this study. The annual output of the two solar technologies is relatively predictable, given a suitable installation as described above. Micro-wind turbines for household application are a relatively young technology at present. Local terrain and mounting height, among other factors, have a significant effect on wind energy potential, and as yet there is little empirical evidence to validate the grid-tied estimates. The estimated range of energy outputs for micro-wind should therefore be viewed as tentative. The results of ongoing UK micro-wind turbine field trials will aid validation of the output estimates presented here.<sup>14</sup>

To place the micro-generator output estimates in context it is useful to consider the quantity of delivered energy used by UK households. In the case of both electricity and hot water, a variety of factors influence annual household energy use including number of occupants; occupant behaviour; household type, size, and location; end-use technologies; and so on. Such factors cause a large range of annual household energy usages. A variety of literature sources suggest that, notwithstanding the wider range possible, annual household electricity use for lights and appliances (i.e. excluding space- and water-heating

applications) typically falls within the range 3000–4000 kWh.<sup>24–27</sup> Space- and water-heating have been excluded for consistency—such requirements are assumed in this study to be supplied by a gas-fired boiler, as discussed below. The selected estimates (Table 1) for annual electricity outputs of the micro-wind turbine and solar PV are equivalent to 22–29% and 43–57% of this usage range, respectively. It should be noted that, in the grid-tied case considered here, a mismatch (in time) between supply and use will necessitate export to the grid. On the basis of a range of literature sources, annual household hot water demands are estimated to be in the range 1200–4000 kWh.<sup>23,28–30</sup> The energy content of annual hot water use (at the tap) was assumed here to be 2900 kWh—near the middle of the range—in accordance with those suggested by the DTI<sup>22</sup> (which provided the performance test results used to generate the output estimates above). The selected output estimate of 815 kWh (Table 1) represents a solar fraction—that is, the percentage of demand supplied by the solar system, of 28%. Lower hot water usage would be likely to reduce the effectiveness of the collector, as tank temperatures will be higher. However, assuming that performance does not vary significantly, low hot water demands could be completely satisfied by a single collector system during at least the summer months. Some energy would be wasted during months in which supply exceeds demand, but annual solar fractions could still be in the range 52–70%. Conversely, solar fractions of 16–24% could be provided for exceptionally high hot water demands.

### 3.3. Micro-generators displacing conventional supply

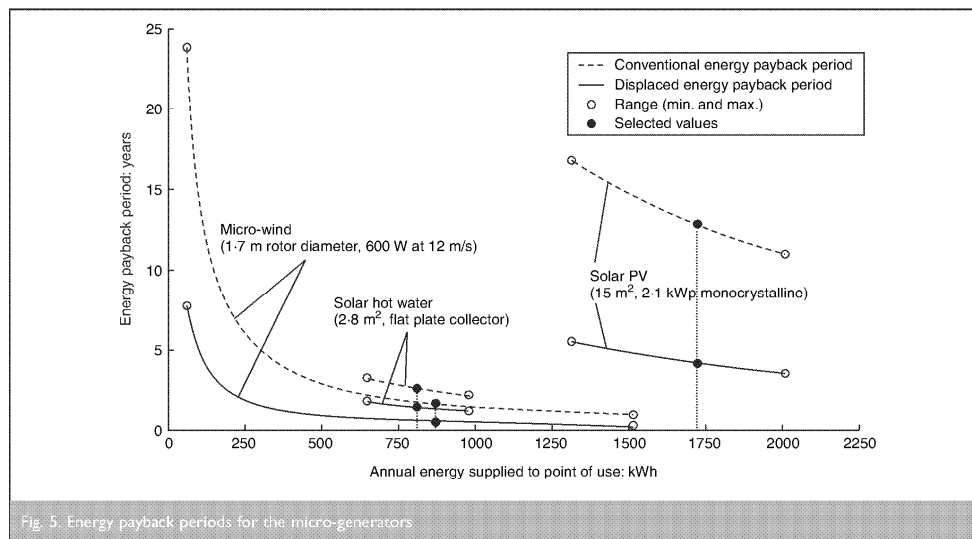
The energy supplied by the micro-generators will displace energy that would otherwise have been provided by conventional means. The form of energy displaced is affected by a variety of technical, economic and political factors including, in the immediate and short term: the electricity and gas markets' operation, the cost of different fuels, the load profiles of end-users, the time of day, the season, and so on. In the long term, the mix of conventional supply technologies will also change. An accurate estimation of the form of energy displaced by a new generator during its life cycle is, therefore, a complex issue. In the case of electricity supply, Britain has a centralised network that is dependent primarily on large-scale fossil- or nuclear-fuelled power stations.<sup>2</sup> An annual snapshot of generator types, with the associated annual resource use of the electricity system, was used to calculate the forms and quantities of energy displaced by the micro-generator. This approach, although simplistic, is pragmatic (and the best that could be done in present circumstances). Domestic space- and water-heating are typically provided together by one on-site central heating system fuelled by a gas boiler (in 2001 approximately 90% of homes in the UK were centrally heated, of which 80% used gas-fired boilers<sup>25</sup>). Therefore the SHW system was assumed here to displace use of a gas-fired boiler (which includes electricity use for pumps and controls, etc.). Since April 2005 UK Building Regulations have required that all new gas-fired boilers installed in England and Wales must be condensing boilers, with seasonal efficiencies of 86% or above (SEDBUK—seasonal efficiency of boilers in the UK—band A or B). A selection of primarily A-rated boilers is being tested in a UK field trial<sup>31</sup> that is focused on assessing the performance of micro-CHP systems. Interim results suggest that the current installations of boilers in homes may frequently perform at 4–5% below their laboratory-based SEDBUK-declared

efficiencies; the average efficiency in the trial being 86% (this is not necessarily due to boilers failing to perform as designed and manufactured, but rather that in actual installations the whole heating system (both in terms of design and commissioning) and subsequent householder setting of controls constrain them to less efficient operation. It is important to note, however, that these are interim results based on monthly rather than annual efficiencies, as none of the boilers has reached a full year's worth of operation. The results should therefore be viewed tentatively. The field trial is ongoing, and is being complemented by another trial run by the UK's EST<sup>31</sup>). The conversion efficiency of boilers currently installed across the UK is, on average, lower than these relatively new boilers. However, 86% is the conversion efficiency assumed here for the calculation of the energy displaced by the SHW system, because during the assumed 25-year lifetime of an SHW system installed today, current boilers (which typically last 15 years) will be replaced, and in accordance with building regulations they will be replaced by (at least) a SEDBUK A- or B-rated boiler.

The use of a micro-generator avoids environmental impacts associated with conventional energy supply. It is by considering these wider energy systems that micro-generators are perceived to 'save' energy or reduce carbon dioxide emissions (along with avoiding other environmental impacts). The whole life-cycle environmental impacts of the micro-generators may therefore be determined by comparing savings ('avoided impacts') with the impacts of their production, use and disposal. This will be discussed further in the LCA section below.

### 3.4. Life-cycle energy implications

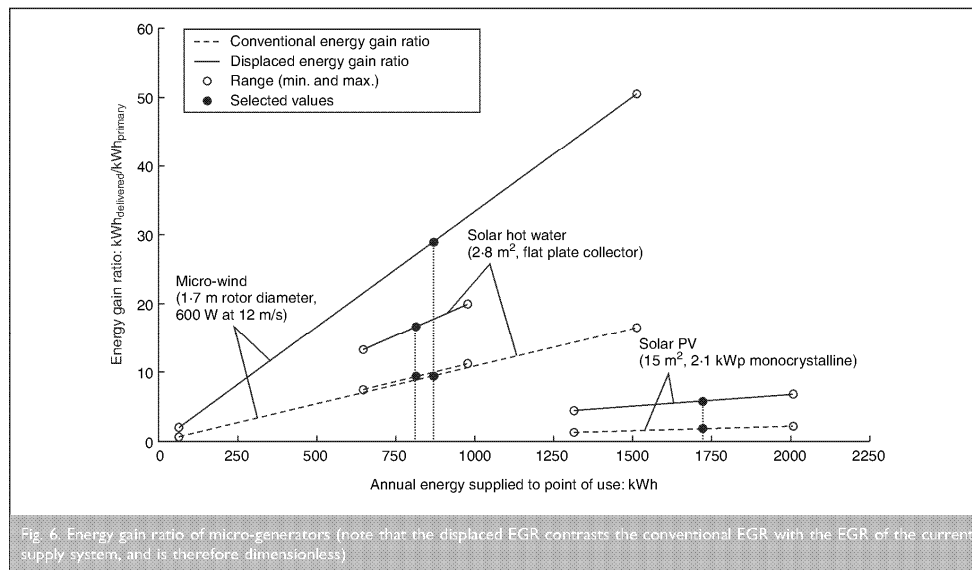
The energy payback period (EPP) is a useful metric that can be derived from an EA, and is analogous to a financial payback period (often termed the 'break-even point'). The EPP represents the number of years that a system must operate until its cumulative energy output equals the 'whole life' or 'life cycle' primary energy requirement, the latter being calculated by way of the LCA software. When the cumulative energy output is accounted for in terms of the absolute quantity of electricity or hot water supplied, the 'conventional' EPP is produced. For example, the primary energy requirement of the micro-wind turbine is approximately 1370 kWh (4930 MJ<sub>LHV</sub>). If the annual electricity supply is 870 kWh (the 'mean open' case; the selected value for this study) the turbine will break even in terms of the energy 'investment' within 1.6 years (Fig. 5). However, this turbine output will displace electricity from the UK's existing supply system. On an annual basis, this system currently requires approximately 3.1 units of primary energy to supply 1 unit of electricity to the end user (Allen *et al.*<sup>14</sup>). It is therefore assumed here that each unit of electricity generated by the micro-wind turbine will displace 3.1 units of primary energy. When the cumulative energy output of the turbine is accounted for in these terms, the 'displaced' EPP is produced (0.5 years in this case). This concept has previously been described as the 'opportunity cost convention', from its precursor in the economic literature.<sup>7,8,14</sup> Fig. 5 shows the variation of the EPP of each micro-generator with annual energy supplied to the point of use. Fig. 5 indicates that the micro-wind turbine and SHW system pay back their whole life, primary requirements faster than the solar PV array, despite lower estimated annual energy supply. This is as a result of their lower primary energy requirements. All three LZC technologies pay back their primary



energy investment well within their estimated lifetimes for the annual outputs selected in the present study.

The energy gain ratio (EGR) is defined here as the ratio of the energy delivered (to point of use) during a technology's lifetime to the life-cycle primary energy requirement. In an equivalent argument to that for the EPP, the 'conventional' EGR simply compares the energy supplied (in the form of either electricity or hot water) to the primary energy required. By contrast the 'displaced' EGR estimates how the technologies perform in comparison with existing supply systems. The latter is therefore dimensionless. For example, as shown in Fig. 6, the displaced

EGR of the 'mean open' micro-wind turbine indicates that it is estimated to supply 29 times more electricity than the existing supply system, per unit primary energy required. The displaced EGRs for the selected outputs of the SHW and PV systems are 17 and 6, respectively. Fig. 6 shows the conventional and displaced EGR of each micro-generator for varying annual energy supply estimates. The significant difference between the conventional and displaced EGRs is attributable to the micro-generators converting freely available, ambient solar or wind-based energy into delivered (utilisable) energy, in contrast to the current electricity supply system that depends primarily on fossil and nuclear fuels. The difference is smaller in the case



Impact category	Unit	'Open' micro-wind		PV		Solar hot water	
		Production	Operation	Production	Operation	Production	Operation
Greenhouse	kg CO <sub>2e</sub>	280	−7520	3760	−24 800	340	−7060
Acidification	kg SO <sub>2</sub>	2	−28	16	−95	2	−7
Eutrophication	kg PO <sub>4</sub>	0.1	−2	1	−6	0.2	−0.6
Heavy metals	kg Pb	0.02	−0.07	0.04	−0.2	0.01	−0.01
Winter smog	kg SPM	2	−20	10	−70	2	−5
Summer smog	kg C <sub>2</sub> H <sub>4</sub>	0.05	−0.5	2	−2	0.1	−2
Energy resources	MJ <sub>LHV</sub>	4930	−143 000	79 400	−473 000	7700	−128 000
Solid waste	kg	220	0	230	0	1	0

Table 2. Comparative environmental impacts of the production and lifetime operation of the systems (CO<sub>2e</sub>: carbon dioxide equivalent; SO<sub>2</sub>: sulphur dioxide; PO<sub>4</sub>: phosphate; Pb: lead; SPM: suspended particulate matter; C<sub>2</sub>H<sub>4</sub>: ethylene)

of SHW, compared with the electricity-generating technologies. This is primarily because the gas-fired boiler, which the SHW displaces use of, has a higher conversion efficiency than the electricity supply system.

The energy analyses presented take no account of the 'quality' of the energy source in a thermodynamic sense. While a detailed exergy analysis, which would include such consideration, was beyond the scope of the present study, it is worth briefly highlighting some pertinent issues relating to energy 'quality'. The SHW system is providing low-temperature hot water to the end user, which has an accordingly low exergy. The EA above has not considered the temperature of delivery of that hot water. In simply counting the energy content—the joules or kilowatt-hours—of the hot water, the temperature of delivery is obscured. For example, given an ambient temperature of 10°C, the energy content of 10 litres of water at 30°C is approximately 840 kJ. In comparison, under similar conditions the energy content of 5 litres of water at 50°C is also 840 kJ. The thermodynamic quality of the latter is greater, while the energy quantity is equal in both cases. In practical terms, the usefulness of SHW to the end user also depends on temperature. For example, the end user may prefer a smaller volume of hotter water rather than a larger volume of cooler water. If that were the case, the auxiliary gas boiler (assumed here as the backup hot water supply system) will be fired up to raise the temperature of the water to the desired level. Hence it is preferable to include an assessment of energy quality supply and demand, alongside the energy quantities.

### 3.5. Environmental life-cycle assessment

The micro-generators were examined to determine their life-cycle impacts. The micro-wind and SHW assessments were based on data gathered directly from the manufacturer. In contrast, the solar PV assessment was based on the results of Wild-Scholten and Alsema.<sup>32</sup> The assessment of all of the systems has focused primarily on the production stage, as there have been few data available for maintenance and disposal of the DERs owing to the relative immaturity of these technologies. For this reason, the data produced are not strictly those of an LCA, as the boundaries have been drawn around the device fabrication and its energy output. Disposal, routine maintenance and distribution have been excluded from this particular study. The exception to this is that the PV system includes an inverter replacement halfway through its 25 year lifetime. In the case of micro-wind one inverter was assumed. Presuming a system

lifetime of 15 years, and given typical inverter warranties of ten years, it was considered likely that an effective inverter could last over this duration. Little information is known about disposal, as few of these systems have yet reached their end of life.

Table 2 shows the comparison of the environmental impacts associated with the production of all three of the DERs together with the avoided impacts associated with the energy produced. For both the micro-wind turbine and the SHW system, the predominant impact associated with the manufacturing phase is the use of aluminium. For the SHW system this is attributable to the metal casing. This provides the system with its rigidity and strength, while maintaining a weight low enough to ensure that extra roof strengthening is not necessary. The casing gives rise to impacts in terms of carcinogens, heavy metals, GHGs and energy resources. Other smaller impacts are associated with the silicon tubing and thermal insulation. Again, the predominant impacts concern heavy metals, carcinogens, energy resources and GHGs.

It appears that the solar PV unit requires significantly more energy (and produces more GHGs) in its production phase than either of the other two systems. It also has significantly higher impacts in terms of the other environmental categories considered. However, the PV system has a larger rated capacity of 2.1 kWp, compared with the 0.6 kW (at 12 m/s) micro-wind turbine. While over its entire lifetime this reduces the impact per unit energy generated, the PV unit generally has higher production impacts than the micro-wind turbine. The production process of high-grade silicon, as used in PV cell manufacture, requires the consumption of a large amount of energy, and this gives rise to these relatively high production impacts.

One of the four long-term goals of the present UK government's energy policy is to 'reduce carbon emissions by some 60% by about 2050'.<sup>3</sup> In this context, it is pertinent to highlight the estimated carbon savings of the three micro-generators. Overall carbon savings are estimated by comparing the carbon emissions emanating during the life cycle of a micro-generator with those avoided (displaced) by the use of that micro-generator. Taking data from Table 2, it is therefore estimated that the micro-wind, solar PV and SHW systems will have carbon payback periods of 0.6, 3.8 and 1.2 years respectively, and will save corresponding amounts of carbon dioxide

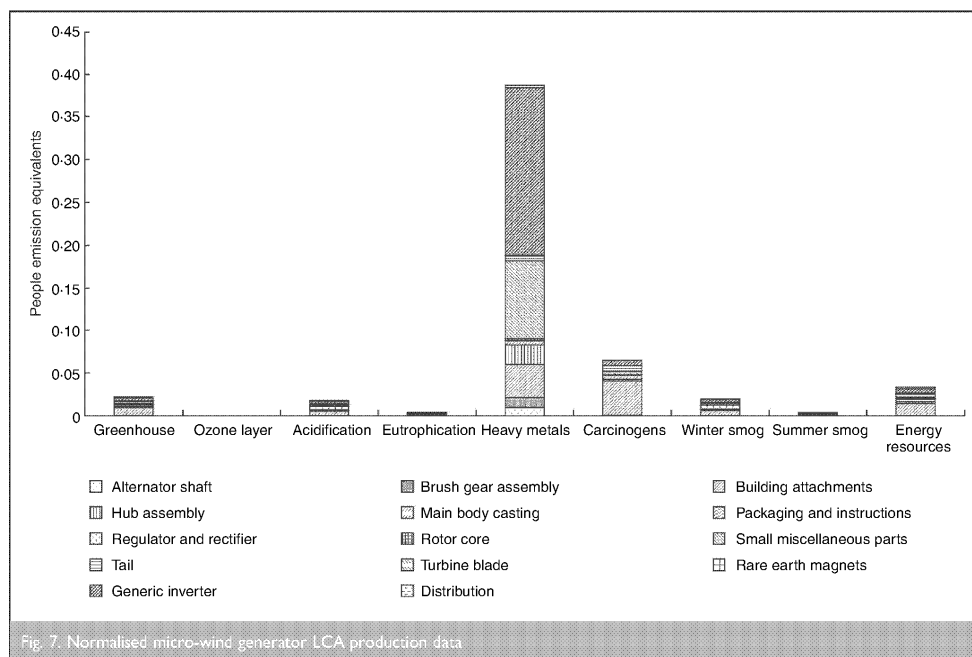


Fig. 7. Normalised micro-wind generator LCA production data

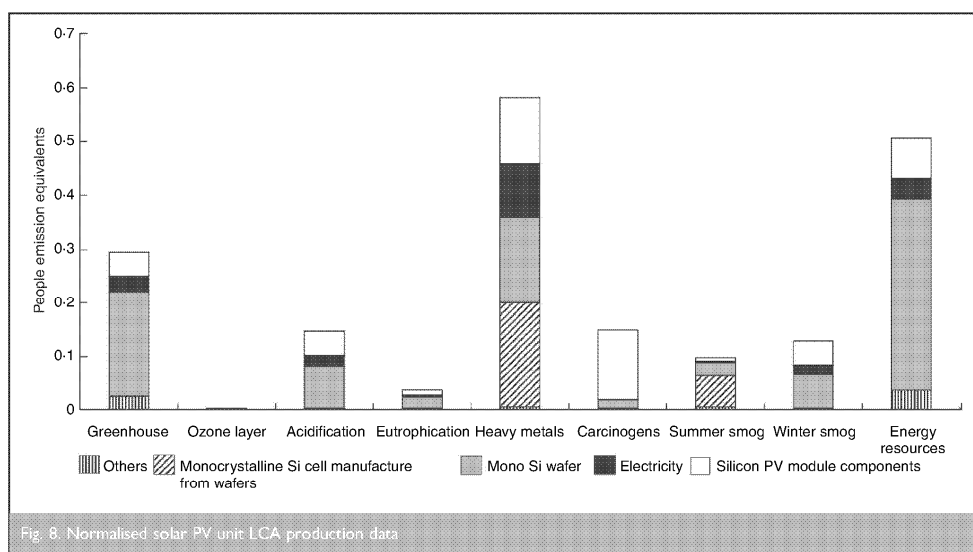
equivalents ( $\text{CO}_2\text{e}$ ) of approximately 7.2, 21 and 6.7 t over the course of their (differing) lifetimes. These figures are associated with lifetime energy supplies: for the micro-wind turbine, 13.1 MWh<sub>e</sub> over 15 years; for the solar PV system, 43.0 MWh<sub>e</sub> over 25 years; and for the SHW system, 20.4 MWh<sub>th</sub> over 25 years. It has been assumed that the electricity micro-generators displace the current, centralised grid, while SHW displaces a modern gas-fired boiler. As previously discussed, these estimates are based on a static, annual snapshot of the conventional supply system. In the case of electricity, this is based on the proportion of electricity supplied annually from different generators with associated fuels. This is a simplistic method, because in reality the generation mix varies both in real time and over the long term, as a result of a range of economic, technical and political factors. The carbon savings figures should therefore be viewed tentatively. While carbon is considered to be a key environmental impact at policy level, it is also important to consider other environmental impacts, such as those also given in Table 2.

Normalised production data for the systems can be used in order to understand which aspects of the DER fabrication have given rise to the above environmental impacts. Fig. 7 shows the normalised LCA data for the grid-tied micro-wind turbine (see also Allen *et al.*<sup>14</sup>). This device, installed in an 'open' environment, is depicted in Fig. 4(a). It indicates that the environmental impact in terms of heavy metals is by far the most significant, although it is worth noting that the actual values shown on the graph are small for all the environmental categories considered. Other comparatively significant impacts arise from the release of carcinogens and the use of energy resources. The main contributor is the inverter, and the aggregated 'small and miscellaneous' parts. To determine the

reason for the impact on heavy metals, the latter element was analysed further. This analysis indicated that the burdens result mainly from aluminium, copper and steel mining, smelting and reprocessing.

The LCA results for the production of the grid-tied solar PV array (shown schematically in Fig. 4(b)) are depicted in Fig. 8. It shows that the most significant impacts from this unit are again in terms of heavy metals and the use of energy resources. In this case data were taken primarily from secondary sources, and it is more difficult to determine the exact point in the production process whence these impacts arise. However, it is seen that many of the impacts arise from the fabrication of the silicon cell wafers. Most of the energy consumption due to the mono-silicon wafer occurs as a result of polycrystalline silicon and associated electricity consumption. Likewise, the generation of GHGs arises from the polycrystalline component and electricity use. The heavy metal pollution emanates from this use of electricity in their production. The silicon PV module components give rise to the generation of carcinogens, which result from the inclusion of copper in the system. Heavy metal pollution arises principally as a result of the use of aluminium in PV module framing.

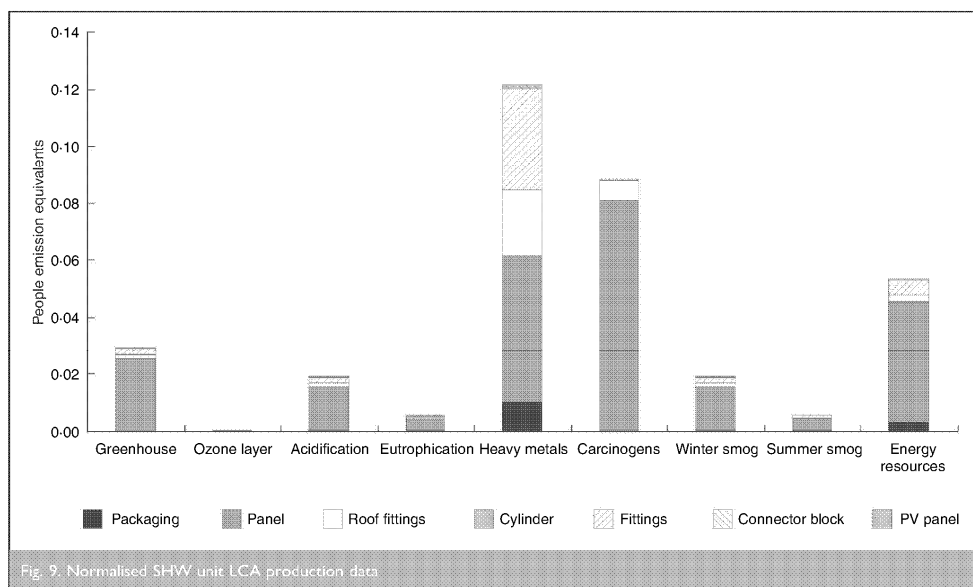
Normalised LCA results for the SHW unit are depicted in Fig. 9. This suggests that the most significant environmental impacts stem from the manufacture of the SHW unit. The largest burdens relate to heavy metals, carcinogens and the consumption of energy resources. The fabrication of the solar panel is seen to have the most significant individual impact in terms of these and other environmental categories. However, it is the main part of the unit (see the schematic representation in Fig. 4(c)), including the metal framing surrounding the panel,



which is aluminium, the silicon piping used to contain the water, the insulating material around the back and sides of the unit, and finally small components, such as screws and rivets. The predominant impact comes from three aluminium components: the sheet, the cover section and the tray. These are the metal components that give the unit its rigidity and strength. Aluminium was chosen by the manufacturer because of its light weight. The unit is supported by the roof, and so extra strength or rigidity is not required. Other smaller impacts are associated with the silicon tubing and the thermal insulation.

### 3.6. Environmental cost-benefit analysis

The present analysis is concerned with assessing the societal cost and benefits of the micro-generators when so-called environmental 'externalities' are evaluated. The financial payback to householders is an issue dealt with in an earlier paper by Butcher *et al.*<sup>1</sup> The total costs of the three micro-generators have therefore been compared with their benefits (value of energy and reduced environmental externalities) over their lifetimes using a discount rate of 3.5%. The latter is the current test discount rate (TDR) employed by the British government for investment appraisal purposes. The total cost



Impact category	Damage factors: £ <sub>2007</sub> /kg	Micro-wind: £ (mean benefit/year)	PV: £ (mean benefit/year)	SHW: £ (mean benefit/year)
Greenhouse: kg CO <sub>2e</sub>	0.02	10.1	40.0	9.4
Acidification: kg SO <sub>2</sub>	2.0	3.5	14.9	0.7
Heavy metals: kg Pb	1098	3.7	18.8	0.4
Winter smog: kg SPM	13.4	17.7	73.8	2.8
Total		34.9	147.4	13.3

Table 3. Environmental externality benefits from installing micro-generators (see Table 2 for abbreviations)

(excluding taxes or grants) of installing the micro-wind turbine was £4397. The PV system was estimated to cost £10442 and the SHW system £3332. These installation costs are solely related to the specific micro-generators assessed here. Other devices, types and sizes may have very different capital costs. The maintenance costs of SHW units are assumed to be near zero, as indicated by the manufacturer. However, solar PV systems need to have their inverters replaced midway through their lifetime. The current cost for the assessed PV system's inverter was taken to be approximately £1000, although this cost is expected to decrease (as a result of economies of scale and learning) into the future, it was adopted here as a conservative cost estimate. The manufacturer of the micro-wind turbine estimated maintenance costs of approximately £40 per year. Given that the electricity output and lifetime expectancy of the assessed micro-wind turbine is relatively lower than that of the PV system, it would be assumed that no change to the micro-wind's inverter is necessary.

Traditional financial investment appraisal takes the direct benefits of installing micro-wind and PV to a householder as displaced grid electricity use, and displaced natural gas for SHW installations. However, the environmental CBA is concerned with the benefits that accrue to society at large, and therefore aims to measure the value of 'electricity' or 'hot water' to UK citizens more broadly. The value of 'electricity' and 'hot water' use to society is not easily definable, because they are really the price paid for electricity or hot water supply plus any consumer surplus remaining. The consumer surplus is simply the difference between the actual price that consumers pay and the price they would be 'willing to pay'. A conservative value (i.e. leaving out the quantification of consumer surplus) of 'electricity' and 'hot water' use in the UK was adopted here by taking the final current average price for electricity (12 p/kWh) and the levelised cost of delivering hot water by way of a condensing gas boiler with 86% efficiency (calculated to be approximately 6 p/kWh).

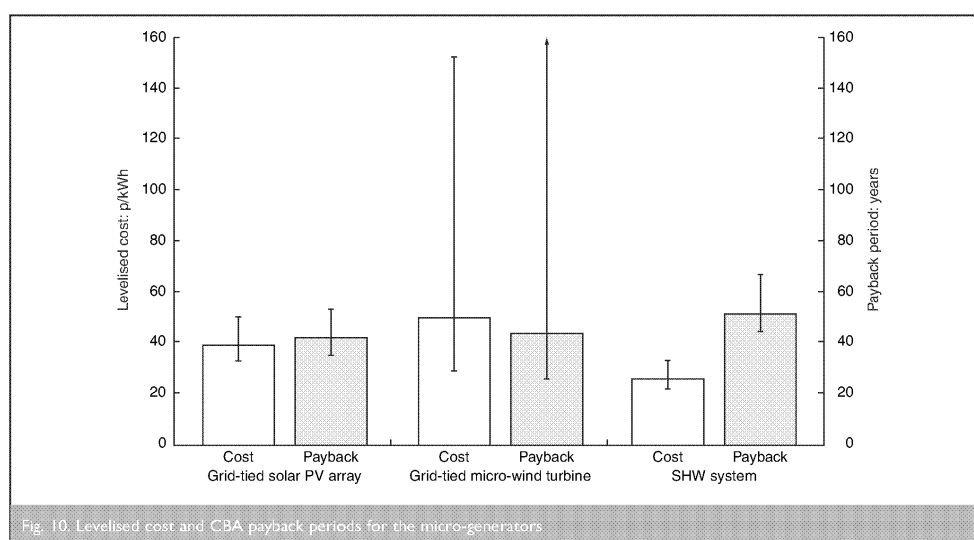
The quantification of environmental externalities was achieved using values extracted from the ExternE study (Dones *et al.*<sup>33</sup>) inflated to present values. These damage factors refer to the most important airborne pollutants, and represent an average location of the emission sources notionally within the former EU15.

However, for carbon emissions a higher range of values was adopted as appropriate in the UK context. These were taken from the equity-weighted values employed by Clarkson and Deyes,<sup>34</sup> approximately £77/tC in 2007 (2000 prices), raised by £1/tC each subsequent year. Table 3 indicates the average estimated annual benefits (£/year) from the reduction of environmental pollutants, as a result of reduced energy (electricity or gas) consumption from installing the DERs. These benefits should be taken as indicative or only representative values.

Table 4 provides the results of this CBA. Economic appraisal of these micro-generators indicates that they are all presently uncompetitive under the current liberalised British (GB) market conditions. The costs significantly outweigh the benefits, even when avoided environmental externalities are included. The estimated costs and benefits indicate that the mean cost-benefit ratio for micro-wind is approximately 1:0.4, while that of the solar PV array is 1:0.41 and the SHW is 1:0.35. Therefore, for every £1 invested in micro-wind, it will currently yield only 40p in benefits to society (41p for PV and 35p for SHW). The levelised costs and payback periods for these systems are depicted in Fig. 10. They are again unattractive in economic terms. PV's economic payback and levelised costs range between 35 and 54 years, and 34 and 52 p/kWh respectively. The CBA payback of the micro-wind turbine is approximately 22 years at the maximum energy output, and 44 years at the mean energy output. This device fails to pay back at the minimum energy output. Its levelised costs range between 28 p/kWh and 151 p/kWh. In the case of the SHW system, the payback and levelised cost values range between 43 and 66 years, and 21 p/kWh and 31 p/kWh respectively. However, it is important to reiterate that the economics of these micro-generators pertain to the specific systems assessed here, and could differ substantially for other types, sizes and manufacturers. Moreover, the uncertainty ranges underlying these economic parameters (see again Fig. 10) are mostly a function of energy output values and therefore subject to their

Mid case (min. to max.)	NPV benefits: £	NPV costs: £	NPV: £	Cost-benefit ratio
Micro-wind (0.1-7 m)	1740 (520 to 3052)	4857	-3117 (-4336 to -1805)	1:0.4 (0.11 to 0.63)
PV (2.1 kWp)	4500 (3358 to 5268)	11 081	-6581 (-7722 to -5813)	1:0.41 (0.30 to 0.48)
SHW (2.8 m <sup>2</sup> )	1170 (923 to 1417)	3332	-2162 (-2408 to -1914)	1:0.35 (0.28 to 0.43)

Table 4. Cost-benefit analysis results



respective energy resource variations (i.e. solar or wind). Furthermore, the environmental externalities quantified form a small, yet considerable, part of the total CBA and are therefore open to additional uncertainties. It is not unlikely that a 'wide range of external costs, as much as five orders of magnitude', could be estimated by adopting different evaluation procedures (as discussed by Hammond and Winnett<sup>5</sup>).

It should be noted that not all of the benefits could be properly quantified in the present study, owing to a lack of information (e.g. concerning the impacts of eutrophication and summer smog). Furthermore, other cost (or benefit) factors, such as system balancing, security of supply, efficiency changes and other system requirements for the uptake of DERs, are dependent on penetration levels and are currently the subject of much research, and could not be included here.

The economics of micro-generators are not presently encouraging. However, cost reductions tend to occur as production volumes increase a phenomenon reflected in so called 'experience' or 'learning' curves (Allen *et al.*<sup>3</sup>). A (global) doubling of production volume typically leads to a reduction in cost to the indicated 'progress ratios' (PRs) percentage value. For the solar PV and SHW technologies, PRs are indicated to be 85% (Enviros<sup>35</sup>) and 92% (Hinnells<sup>36</sup>) respectively, while micro-wind has a PR of 72% (EST *et al.*<sup>4</sup>). By comparison, established conventional energy technologies have PRs of above 95% (Allen *et al.*<sup>3</sup>). Micro-wind and solar PV, in particular, have favourable PRs, indicating significant cost reduction potential. The EST *et al.*<sup>4</sup> project annual growth rates (%) in double digits for most DERs over the next few decades, which would be likely to result in significant cost reductions. However, in the near term, these decentralised energy sources are likely to remain uncompetitive in a liberalised marketplace dominated by conventional energy supply systems. Government-initiated support is required to encourage sufficient uptake for this to occur, especially in the short term. Only then will they be favourable in comparison with separate supply by way of the electricity or natural gas

networks, enabling them to fully deliver their undoubted environmental benefits (see Butcher *et al.*<sup>1</sup>). There remain, at present, substantial barriers to significant production increases and associated cost reductions (see Allen *et al.*<sup>3</sup>).

#### 4. CONCLUDING REMARKS

A range of integrated appraisal techniques have been employed to study the comparative performance of three micro-generator options in a UK context: a micro-wind turbine, a solar PV array and an SHW system. These devices have been proposed as possible DERs for 'low-carbon' buildings. It has been noted that, in the case of micro-wind and SHW, there are a range of technologies in the marketplace that are likely to perform differently to the specific generators studied here. The generators that have been considered are not, therefore, necessarily representative of each type of technology. Energy, environmental impact and economic analysis methods, employed on a life-cycle ('full fuel cycle') basis, have been described. They can be viewed as being 'integrated' in the sense that they are interconnected, but yield differing implications for the take-up of the micro-generators in terms of a 'sustainability framework' (see Hammond and Winnett<sup>5</sup>). They are interrelated in the sense that life-cycle EA was one of the precursors for environmental LCA,<sup>5</sup> and is typically performed in parallel with environmental appraisal in most modern LCA software packages. Both EA and LCA avoid the examination of products on a 'subsystem' basis, whereby only one part of the life cycle is examined. They can also be employed, as with the present evaluation of residential micro-generators, to estimate impact inventories which can then be coupled with environmental CBA to yield their environmental costs. Such methods help to provide a performance 'snapshot' in time, based on quantitative evaluations. The approach encapsulates the 'whole systems' implications of the selected DERs, although there are other considerations appropriate to providing a complete appraisal.

On an annual basis, it has been estimated that the micro-wind turbine (installed in an 'open', as opposed to an 'urban',



environment) and solar PV array will provide 870 and 1720 kWh of electricity in the (mean) average installation, respectively. While annual household electricity usage is known to vary widely, these estimated outputs are equivalent to 22–29% and 43–57% respectively of the indicative values of 3000–4000 kWh (excluding space- and water-heating). It has been noted that, in the grid-tied case considered here, some of this electricity would be exported to the local network. Similarly, it has been estimated that the SHW system will provide approximately 815 kWh/year of hot water in an average installation, which is 28% of the assumed annual energy demand. There is a good deal of scope to reduce demand from the values considered here, through energy efficiency and demand reduction measures. Such measures should be adopted before installation of a micro-generator, the relative contribution of which will then accordingly increase. All micro-generators considered pay back their energy investments well within their lifetimes, given the appropriate installations outlined. Considering the fossil fuel energy savings that they offer, the 'displaced' EPPs are estimated as 0.5, 4.2 and 1.5 years for the micro-wind turbine, solar PV array and SHW system respectively. Over their lifetimes, these technologies are estimated to supply an amount of delivered energy that corresponds to 29, 6 and 17 times that which would be supplied by conventional means, per unit of primary energy required. It has been highlighted that, while outside the scope of the present study, the thermodynamic quality of energy flows should be considered alongside the quantity of those flows. This may be achieved by an exergy analysis.<sup>2,5,6</sup>

One of the four long-term goals of the present UK government's energy policy is to 'reduce carbon emissions by some 60% by about 2050'.<sup>3</sup> In this context, it is pertinent to highlight the potential carbon savings of the three micro-generators studied. It has been estimated that the micro-wind, solar PV and SHW systems will have carbon payback periods of 0.6, 3.8 and 1.2 years respectively, and will save approximately 7.2, 21 and 6.7 t of carbon dioxide equivalents over the course of their (differing) lifetimes. It has been assumed in this study that the electricity micro-generators displace the current, centralised grid, while SHW displaces a modern gas-fired boiler. These estimates, along with all estimates relating to the displacement of energy from conventional sources, are based on a static, annual snapshot of the existing supply systems. This is a simplistic view, and the carbon- (and energy-) related indicators should therefore be viewed tentatively. Furthermore, while carbon is considered to be a key environmental impact at policy level, it is also important to consider other environmental impacts associated, such as those also discussed within this study.

In terms of the environmental LCA, both the manufacture of the solar thermal and micro-wind turbine give rise to environmental impacts associated principally with their utilisation of aluminium. This material is often chosen owing to its high strength-to-weight ratio, but it also gives rise to heavy metals, carcinogens and contributes to some types of smog, as well as using significant amounts of energy (it has a very high energy intensity; GJ/t). These environmental impacts, estimated by way of LCA software, could easily be reduced by the greater use of recycled aluminium. The solar PV array has rather higher impacts emanating from its fabrication, but this is offset by the higher energy generation during operation.

Cost-benefit analysis has been utilised to communicate more clearly the overall trade-offs involved in installing the three micro-generators. The most obvious rationale for installing these systems is related to the abatement of GHGs and other pollutants. The quantification and internalisation of the costs for these 'externalities', with all their uncertainties and limitations, presents a more complete picture of the DERs. This environmental CBA indicates a mean cost-benefit ratio of 1:0.4 for micro-wind, 1:0.41 for PV and 1:0.35 for SHW. The results suggest that the three micro-generators are all uncompetitive under the current liberalised GB market conditions, even allowing for environmental externalities. Increased production volumes and technical improvements in the next generation of devices, such as their manufacturing processes and operational efficiencies, are necessary to improve their economic performance. Government-initiated support is required to encourage sufficient uptake for this to occur, especially in the short term. Only then will they be favourable in comparison with separate supply by way of the electricity or natural gas networks, enabling them to fully deliver their undoubted environmental benefits (see Butcher *et al.*<sup>1</sup>). This is one of the 'realities' in moving towards low-energy/low-carbon buildings. Allen *et al.*<sup>3</sup> have described in some detail both the prospects for, and barriers to, the implementation of residential micro-generation technologies on a larger scale.

#### ACKNOWLEDGEMENTS

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# Energy analysis and environmental life cycle assessment of a micro-wind turbine

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**Abstract:** The life cycle energy use and environmental impact of an installed micro-wind turbine for domestic (residential) electricity generation has been determined. The turbine examined was a horizontal-axis wind turbine, which has a rotor diameter of 1.7 m, a power rating of 600 W at 12 m/s, and an assumed lifetime of 15 years. The system boundaries for the study encompass energy and material resources in the ground and extend to the point of delivery of electricity. The energy output of the turbine in different terrains has been estimated via a dataset of hourly measured wind speeds, and the environmental impact of producing and maintaining the micro-wind turbine was determined. The environmental performance of the turbine was assessed by assuming that each unit of electricity generated displaces (avoids the use of) a unit of grid electricity. The whole life cycle performance of a micro-wind turbine was found to be dependant on a number of factors, primarily the geographical positioning of the turbine, the available wind resource, and the use of recycled materials within the production of the microturbine.

**Keywords:** energy analysis, life cycle assessment, micro-wind power, urban environments, wind resource

## 1 INTRODUCTION

### 1.1 Background

The current electricity supply system in the UK is highly centralized, and relies heavily on the combustion of fossil fuels that produce pollutants including greenhouse gases (GHGs). Approximately 38 per cent of current UK GHG emissions can be attributed to the energy supply sector (this includes electricity generation, the use of fossil fuels for petroleum refining, and the production of coke and solid smokeless fuels) [1]. Losses in the electricity supply system presently amount to around 65 per cent of the primary energy input, 58 per cent of which is due to heat wasted during centralized production while transmission and distribution losses amount to approximately 7 per cent [2]. Clearly, thermodynamic constraints prevent elimination of these losses completely. However, decentralized technologies, such as combined heat

and power (CHP) plants, can dramatically increase the energy efficiency of fossil fuel use by capturing some of the rejected heat and supplying it for space and water heating. Heat and electricity can also be produced locally by renewable sources, such as solar thermal systems, solar photovoltaics, and micro-wind turbines.

Decentralized or distributed energy supply refers to the generation of energy close to the point of use. It can denote a range of generator sizes; from community or district-level down to individual households. Micro-generation is defined in Section 82 of the Energy Act (2004) as 'the small-scale production of heat and/or electricity from a low carbon source' [3]. It has further been classed as anything below 50–100 kW, with most household electricity supply installations being below 3 kW<sub>e</sub>; and slightly larger for heat supply. It has recently been suggested that microgeneration could provide 30–40 per cent of the UK's electricity needs by 2050 [4]. However, Allen *et al.* [5] have recently suggested that significant barriers to the increased utilization of microgeneration exist in the UK.

There are three broad categories of turbine available: horizontal-axis wind turbines (HAWTs);

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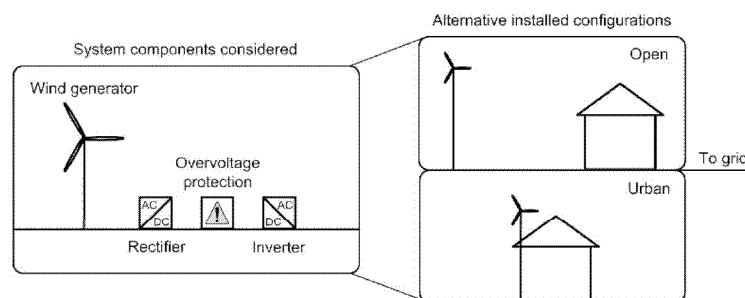


Fig. 1 Grid-connection schematic

vertical-axis wind turbines; and building augmented wind turbines. The latter category further breaks down into three sub-categories: turbines situated on a building; turbines placed in a duct through a building; and turbines located between diffuser shaped buildings [6]. The most common type in the UK is the HAWT. Bahaj *et al.* [7] suggest that for open areas with preferable wind conditions, and with suitable mounting heights, there is a potential for micro-wind turbines to make a significant impact on domestic electricity generation. Micro-HAWTs with roof-mounting options have recently become available but there is doubt, fuelled by the current lack of empirical proof, about their suitability for roof-mounting particularly in an urban environment (see references [7] to [9]).

## 1.2 The present study

The aim of this study was to assess the energy performance and environmental impact of installing a micro-wind turbine for domestic (residential) electricity generation. Life cycle assessment (LCA) methods were employed using a commercial software package. The turbine examined was a HAWT, which has a rotor diameter of 1.7 m, a power rating of 600 W at 12 m/s, and an assumed lifetime of 15 years. The energy output of the turbine in different terrains was estimated via a dataset of hourly measured wind speeds, and the environmental impact of producing and maintaining the micro-wind turbine was determined. Data for the material components and fabrication of the microturbine were obtained from a manufacturer and augmented, where required, with generic industry data. In the absence of required data, an estimate was made using published LCAs, data held within the LCA software database, and other available industry data. The environmental impact of the turbine in use was then assessed by assuming that each unit of electricity generated displaces (avoids the use of) a unit of grid electricity. The effect of this displacement will, of course, vary with time, albeit slowly (tens of years),

as the mix of electricity generation technologies that comprise the electricity network changes. The system boundaries for the study encompass energy and material resources in the ground and extend to the point of delivery of electricity. The disposal of the wind turbines has not been included in this particular study, because these systems are relatively new and there is little data available about their disposal.

Figure 1 shows the assumed installation of the turbine. The estimate incorporated losses associated with the generator and rectifier (which are included in the turbine's power curve), and the inverter (taken from manufacturer's datasheet). This facilitates the indication of the energy provided to the household or grid.

## 2 ENERGY ANALYSIS OF MICROWIND

Energy supplies are defined as either primary or secondary [10]. Primary energy is drawn directly from natural reserves or flows such as crude oil and coal, while secondary energy is produced from derivatives of primary commodities, for example, petrol and coke. In order to determine the primary energy inputs needed to produce a given amount of product or service, it is necessary to trace the flow of energy through the relevant industrial system. This is based on the first law of thermodynamics, i.e. the principle of conservation of energy, or the notion of an energy balance applied to the system. The techniques of first law analysis have been widely used since the first oil crisis of the early 1970s, and became known as energy analysis or accounting in the late 1970s [11–13]. An important distinction between energy analysis and economic analysis is that the former method is 'descriptive' while the latter is 'normative' or 'prescriptive' [14]. Energy analysis describes the energy implications of different options but does not decide the optimal course of action, and therefore should be used as one part of an inter-disciplinary toolkit within a general systems' framework for energy system assessment [15].

## 2.1 Estimating the energy output of the turbine

In order to estimate the amount of energy generated by the turbine, the amount of potential energy in the wind must be determined. The gross instantaneous power of the wind,  $P_G$ , may be determined as follows

$$P_G = \frac{1}{2} \rho A u^3 \quad (1)$$

where  $\rho$  is the density of air,  $A$  the cross-sectional area in which the air is passing through, and  $u$  the velocity in metres per second [16].

It is important to note the cubic relationship between wind velocity and power output, and the square relationship between turbine diameter (which appears in the cross-sectional area term) and power output; these are the dominant factors. The density of air is a function of the air pressure and temperature, both of which vary with altitude and broad meteorological conditions. The ISO Atmosphere model [17] was applied to calculate air densities for the altitudes of the UK weather stations used for wind speed data (minimum: 4 m, mean: 110 m, maximum: 395 m), and the micro-wind turbine energy output estimations adjusted accordingly. The greatest reduction in air density (and corresponding energy output) due to altitude was 4 per cent from the standard 1.225 kg/m<sup>3</sup>.

Betz [18] established that the maximum power that can be extracted from the wind is 16/27 (59 per cent) of the gross power  $P_G$  [16]. Owing to aerodynamic and power conversion losses, turbines currently extract less than the Betz limit. Power curves are commonly used to communicate the power generation capabilities of a turbine with varying wind speed. Fig. 2 shows a representative micro-wind turbine power curve, compared with the gross power available and that available according to the Betz law.

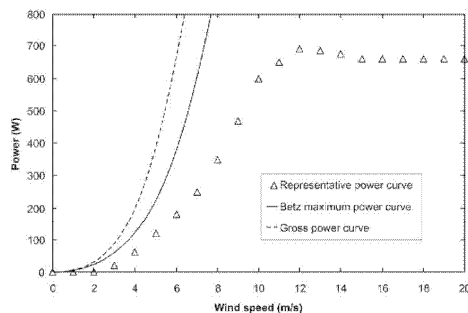


Fig. 2 Typical power curve for a micro-wind turbine, compared with gross power available and the Betz limit. Sources: manufacturer's datasheet; Betz [18]

The British Standard for determination of turbine power curves (BSI [19], pp. 15, 74) states that turbine output power for small wind turbines 'shall be measured at the connection to the load', and that power curves should incorporate all positive and negative instantaneous power peaks (i.e. include any parasitic losses). The output estimations assume that the power curve used in this study has been produced in accordance with the standard, and therefore it incorporates all losses up to the point of inversion to the household electricity supply.

A knowledge of the power producing capability of the micro-wind turbine enables an estimate of energy outputs, when combined with an assessment of the available wind resource. The structure of the wind resource in different terrains is therefore discussed below, followed by available methods for representing that resource.

## 2.2 The structure of the wind resource

The structure of the wind within urban environments is a highly complex phenomenon. This is of particular interest when considering the roof-mounting of micro-wind turbines where the turbulence fields are at their most complicated.

Globally, winds are caused by pressure gradients generated by the differential heating of the Earth's surface by the Sun, and are further affected by the Earth's rotational motion. The lower region of the atmosphere is known as the atmospheric boundary layer, and within this the shear stresses caused by the Earth's surface extract momentum from the wind, and cause a variation of velocity with height. Topography, surface roughness, and the possible occurrence of thermal stratification can have significant effects on the structure of the wind within the atmospheric boundary layer [20]. Urban environments typically have the greatest surface roughness, and climatological processes in such environments are accordingly complex.

Urban climatology research has defined a number of distinct layers within the atmospheric boundary layer (termed urban boundary layer in such literature), which are characterized by differing scaling properties. The urban canopy layer, occurring approximately from ground to roof level, is controlled by the microscale effects of site characteristics. Encompassing this zone (and above) is the roughness sublayer (RSL), in which interacting wakes and plumes of heat, humidity, and pollutants are introduced by individual roughness elements [21]. The turbulence field within this layer is often not horizontally uniform, even on a time average, and must be considered three-dimensional [22]. The height of the RSL is a subject of much debate, but Roth [22] proposed that it has

dimensions of the order of tens of metres and, for the studies he reviewed, extended to about 2.5–3 times the average height of the buildings. Turbulent mixing tends to cause the effect of any significant roughness elements to be lost at higher levels, and creates a layer known as the constant flux layer (CFL), in which turbulent fluxes are constant with height [21]. Little is known about this region in urban areas, in part due to the height restrictions of measurement towers. Above the CFL is the mixed layer, in which turbulent properties are probably independent of surface roughness [22].

### 2.3 Turbulence intensity of the prevailing wind

Healey [23] (in reference [24]) found that the excess kinetic energy associated with turbulent fluctuations may be significant in comparison with the energy estimated on an hourly mean. This depends on the turbulence characteristics of the site and the turbine response time. However, the ability of a turbine to extract any of this extra energy is an area of relatively little empirical knowledge with respect to micro-wind turbines. HAWTs, for example, need to yaw (rotate about their vertical-axis) in order to face the oncoming wind so that they can extract energy. Higher levels of turbulence typically lead to more frequent changes in wind direction and speed, and a HAWT's ability to track the wind direction (along with its other dynamic response characteristics) therefore becomes increasingly critical to energy capture.

The instantaneous wind speed for a steady flow, in the direction of the free-stream ( $x$ -direction), can be described as a time-mean wind speed,  $\bar{u}$ , plus a fluctuating wind component  $u'$

$$u = \bar{u} + u' \quad (2)$$

The root mean square of  $u'$  provides a measure of the amplitude (or intensity) of the fluctuations, and is denoted as  $\hat{u}$ . Instantaneous wind speeds in the perpendicular  $y$  and  $z$  directions can similarly be defined as  $v$  and  $w$ , with equivalent time-mean and fluctuating components. The relative turbulence intensity in direction of the predominant flow is then commonly defined as

$$I = \frac{\hat{u}}{\bar{u}} \times 100 \quad (3)$$

A method currently adopted by some practitioners within industry is to incorporate this measure of turbulence when estimating the wind resource. They adopt the turbulence intensity as a form of heuristic safety factor, reducing the output estimation by its percentage value. Bergrey Windpower [25], for example, recommend a turbulence intensity factor (and hence reduction in output prediction) of 15 per cent for most

site-assessment situations. Note that output is therefore inversely proportional to turbulence intensity in these output estimations. It is generally observed that, for a given height,  $I$  is up to twice as much over an urban surface than a corresponding rural reference value. This is not so much a result of increasing  $\hat{u}$ , but due to retardation of the flow close to the roughness (a reduction of  $\bar{u}$ ) [22].

Roth [22] reviewed 14 studies concerning turbulence in the urban environment, and provides an empirical relationship between turbulence intensity and height above ground within an urban environment, for each perpendicular component of the flow. Fig. 3 highlights that the mounting-height of a turbine within an urban environment has a significant affect upon the longitudinal turbulence intensity. In the worst case, a turbine might be mounted at average-roof level within an urban environment. Fig. 3 suggests that this corresponds to a turbulence intensity value of approximately 50 per cent, compared with an estimation based only on an hourly mean wind speed.

Turbulent wind flows, as highlighted above, occur at higher frequencies than hourly averaged wind speeds. Thus the present methodology, while used within industry, is an approximation that requires validation for micro-wind-scale application. It is arguably

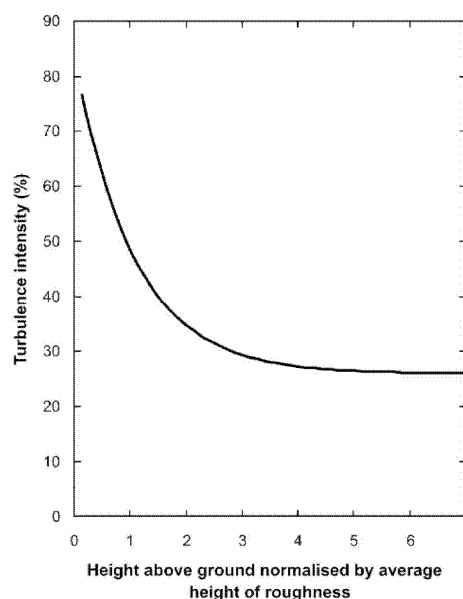


Fig. 3 Turbulence intensity as a function of height in urban environments, in the direction of the free-stream. Source: Roth [22]

conservative as it assumes turbulence simply reduces power output with no allowance for any possible increase.

## 2.4 Representation of the wind resource

There are a number of sources of wind resource information available, which have varying degrees of accuracy and applicability for micro wind output estimation. For an initial estimate, a mean wind speed for a given time period (e.g. on an annual basis) can be utilized and combined with a Rayleigh or Weibull frequency distribution to statistically describe the wind resource [26, 27]. Sources for UK annual mean wind speeds include the UK Department for Business, Enterprise and Regulatory Reform's 'NOABL' database [28] and the Danish Risø National Laboratory's 'European Wind Atlas' [29]. These sources do not directly take local effects (such as surface roughness) into account, and hence such considerations must be incorporated into a resource assessment. For roof-mounting of micro-wind turbines this is particularly problematic, as relatively little is known about the structure of the wind resource in urban areas. It is generally recommended that initial resource estimates based on these data sources are followed by on-site measurements to allow for more accurate assessments.

Here, the preferable option of directly measured wind speeds was applied, using measured hourly mean wind speeds from Met Office weather stations (filtered to ensure that only values quality checked by the Met Office were included in the final dataset). It was assumed that the micro-wind turbines were mounted at the height of the anemometer. The standard exposure of Met Office anemometers is 10 m above level, open terrain [30]. While this is usually achievable in rural environments, it is often impossible within urban areas as they are commonly mounted upon the town/city weather centre building (albeit with the aim of representing the locality as accurately as possible). Therefore, it was assumed that estimates based upon weather station data from open, rural terrain represent turbines mounted upon 10 m masts away from rural households, while those in urban terrains represented turbines mounted upon buildings.

## 2.5 Inverter performance

Grid-connected micro-wind turbines are commonly installed with an inverter (DC to AC converter), in order to produce electricity that is compatible with the power network; this is the case for the turbine considered here (Fig. 1). The turbine is used in conjunction with a permanent magnet, brushless generator. It generates varying frequency, varying

voltage three-phase AC. A rectifier then converts this to varying voltage DC, prior to inversion to grid-compatible AC (fixed-frequency, fixed-voltage, single-phase). Inverters are required to shut-down in the event of: high/low grid AC-voltage, high/low grid frequency, grid failure, or inverter malfunction.

The efficiency of a pulse width modulation inverter (such as that installed with the turbine) is affected by switching losses, the internal power consumption of other onboard electronics, and conduction losses. The switching frequency of the semiconductor devices within the inverter is determined by the manufacturer during design, and is therefore constant during operation. The inverter consumes approximately 4 W during operation, and 0.1 W in standby [31]. Conduction losses, however, are affected both by modulation index (wind turbine power output) and loading power factor (the household load or grid). For low current applications such as grid-tied micro-wind turbines (micro-generators are limited to 16 A by G83/1), the influence of the loading power factor on conduction losses is small, and was therefore assumed constant during modelling ([32]; A.M. Massoud, University of Strathclyde, 2007, personal communication). It was assumed here that the only variable affecting the conduction losses is the wind turbine power output, which determines the operational power and hence efficiency of the inverter. The efficiency of the inverter varies with operational power as indicated in Fig. 4 [31].

At wind speeds below the cut-in speed of the turbine ( $\sim 2$  m/s), the micro-wind turbine will not operate and hence the inverter will be in standby mode, consuming 0.1 W. The turbine will generate power above the cut-in speed and, if the rectifier output of DC voltage is above the inverter's requirements for onboard electronics, the inverter will operate, consuming 4 W as indicated above. Shut-down events, such as high/low grid voltages were not included in the present estimation procedure.

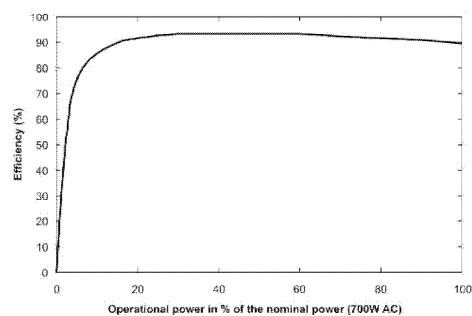


Fig. 4 Inverter performance characteristics. Source: extracted from manufacturer's datasheet (SMA [31])

## 2.6 Estimating energy outputs from micro-wind generators

In order to estimate the energy outputs for a variety of geographical sites, hourly mean wind speed data recorded between 1990 and 2006 from 26 sites (totalling approximately 2.3 million hours of filtered data) were combined with a published power curve and grid-tie inverter characteristics. A total of 18 of these sites (187 combined years or 1.64 million hours of data) were categorized as 'open', i.e. well exposed and mostly rural terrain. Eight sites were categorized as 'urban' (76 combined years or 0.67 million hours of wind speed data). It was assumed that the generator would be installed at the anemometer position, and hence no height adjustment of the observed wind speed data was necessary. For the 'open' sites, the wind resource approximately represents that available to a turbine mounted upon a 10 m mast away from rural households, and for 'urban' sites, the resource represents that available to an urban turbine mounted upon a building. The estimates were corrected for the turbulence intensity, whose value was determined from the academic and public literature, and reduced by an availability factor that assumed that the micro-wind turbine operated for 90 per cent of the time (to allow for breakdowns/maintenance). It was assumed that all the energy produced by the turbine was either consumed within the household or exported to the grid. If exported, it was assumed that the electricity was consumed locally, and hence transmission/distribution losses were considered negligible.

The dynamic response of the micro-wind turbine and inverter, as a system, will be of a higher frequency than the 1/3600 Hz (hourly) data used within this study. The characteristics of the inverter in terms of its start-up and shut-down procedures in response to changing wind speeds (and corresponding power production by the micro-wind turbine) could be critical to energy yields. Particularly in areas of low wind speeds (where the power input to the inverter could be frequently oscillating around the critical start-up/shut-down condition), the feasibility of grid-tying micro-wind turbines may be significantly affected by the interaction between the turbine and the inverter, and further research is required in this area. The results of ongoing field trials, due to report in 2008, will be useful to compare the current output estimations with measured data [33, 34].

## 2.7 The energy performance of the micro-wind turbine

The energy output of a wind turbine (as discussed above) will vary with geographical location, meteorological conditions, and local positioning of the turbine. The electricity actually produced will further depend

on the electrical characteristics of the system components. On the basis of described on-grid configuration, the energy output estimates for the turbine over a range of open and urban terrains is summarized in Fig. 5. The capacity factors, which represent the actual energy production compared with that achieved if the turbine were to output its rated power continually, are also indicated in Fig. 5.

The mean annual wind speeds in the open environments ranged between 2.8 and 7.8 m/s, while those in urban environments ranged between 2.3 and 5.2 m/s. Note that the urban wind speeds were considered to be more heavily affected by turbulence (power robbing effect of 50 per cent, compared with the 15 per cent value used for open environments). The effects of turbulence on micro wind energy outputs are not well understood, and further study is required in this area.

Figure 6 shows that the average household electricity consumption was approximately 4500 kWh over the period 2000–2005, and that this figure has been broadly constant since the 1970s (DBERR [35] and DCLG [36]). Thus, the mean energy output from the micro-wind generator over an open domain (870 kWh) is approximately one-fifth of this average electricity demand. In an urban setting, the mean turbine output (164 kWh) is approximately 1/25th of the demand. These figures highlight the importance of energy efficiency and demand reduction, alongside appropriate installation of a turbine, if a significant proportion of demand is to be supplied by the turbine. Allen *et al.* [5] discussed the main microgeneration options available to householders, including micro-wind turbines, and concluded that they are mostly financially unattractive under current UK market conditions (having long financial payback periods). It is important, however, to consider the environmental impact of installing the turbine alongside the proportion of electricity demand that can be supplied and the financial return this

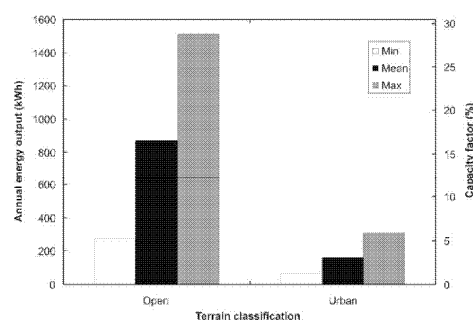


Fig. 5 Annual energy output estimations for different terrain classifications



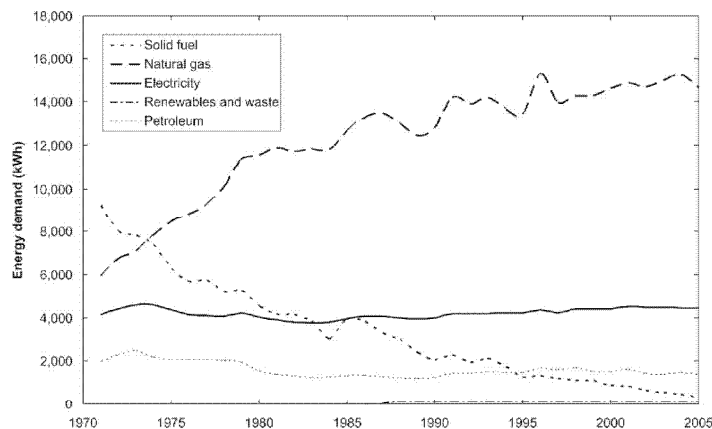


Fig. 6 UK domestic sector energy consumption per household, by fuel type (1971–2005).  
Source: DBERR [35] and DCLG [36]

presents. This can be evaluated using LCA and additional energy analysis techniques, both of which will be discussed below.

### 3 ENVIRONMENTAL LCA

#### 3.1 LCA methodology

Life cycle assessment is an environmental management tool that examines the contribution of a product or system towards predefined environmental impacts (for example, GHGs or solid waste), over its lifetime through production, use, and disposal. The methodology of LCA has been standardized via Society of Environmental Toxicology and Chemistry guidelines subsequently codified in ISO Standards (ISO 14040 and 14044). There are four main stages in the LCA process: goal definition, inventory, impact assessment and improvement assessment, and interpretation. These are described below and shown in Fig. 7.

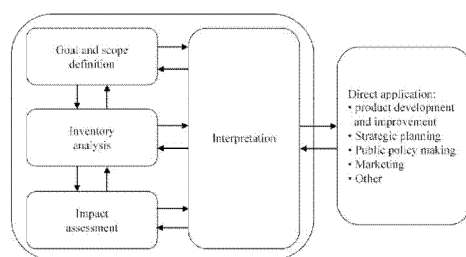


Fig. 7 Main stages in LCA (ISO 14040 and 14044)

*Goal definition* is the stage in which the scope of the project is outlined. Here, the study boundaries are established and the environmental issues that will be considered are identified.

The *inventory* stage is where the bulk of the data collection is performed. This can be done via literature searches, practical data gathering, or through the use of software. Most commonly, a combination of the three is adopted.

*Impact assessment* is where the actual effects on the chosen environmental issues are assessed. This stage is further subdivided into three (or four) elements: classification, characterization, (normalization) and valuation.

- (1) Classification is where the data in the inventory are assigned to the environmental impact categories. In each class there will be several different emission types, all of which will have differing effects in terms of the impact category in question.
- (2) A characterization step is therefore undertaken to enable these emissions to be directly compared and added together. This step yields a list of environmental impact categories to which a single number can be allocated.
- (3) These impact categories are very difficult to compare directly and so the valuation step is employed so that their relative contributions can be weighted. This is subjective and difficult to undertake and many studies omit this step from their assessment. The ISO standards state that it should not be used in any comparative or decision-making study.
- (4) Instead of valuation many people employ normalization as an intermediate step.

*Improvement assessment* is the final phase of an LCA in which areas for potential improvement are identified and implemented.

In this study, the data have been normalized with respect to average European emissions. This can be achieved using the notation of 'people emission equivalents', which can be defined for the present purposes as follows

$$\text{European emissions per capita} = \frac{\text{Total European output in each emission category}}{\text{Population of Europe}} \quad (4)$$

$$\therefore \text{People emission equivalents} = \frac{\text{Emissions from the process studied}}{\text{European emissions per capita}} \quad (5)$$

This allows a comparison of the importance of each category to be made without attributing subjective valuation. Within this study, the LCA software package SimaPro v7.1 was used [37]. This software enables the manipulation and examination of inventory data in accordance with the LCA ISO Standards. It also contains a wide variety of LCA databases, including the EcoInvent Database [38].

### 3.2 The environmental burdens attributed to micro-wind turbine manufacture and transportation

The material data collected for the turbine were modelled and analysed using the LCA techniques

previously described. Figure 8 shows the characterized data for the production of the micro-wind generator, including materials, processes, and transportation of the materials and components to the turbine factory. Energy and water use from the factory has not been included because it was not available. As only the assembly takes place in the factory there would only be heating and lighting to be considered. Although it is probable that this would make little overall impact, it is desirable to collect this data in the future for the sake of completeness and certainty. Once the micro-turbines have been produced they are usually ordered on line and then delivered to the customer, or taken to the customer by a company representative. It has been assumed, therefore, that the generator leaves the factory in a postal delivery van or a company van and that the average distance travelled is 400 km. This will differ from manufacturers whose turbines are collected by truck from site, taken to distribution centres, then to retail shops and then taken home either by car or by van. Within this case study the term 'production' when associated with the turbine will also include the transportation of the turbine to the customer.

It can be seen from Fig. 8 that the main contributor to each environmental impact category is the component used to attach the turbine to the building. This is the heaviest part of the turbine and in the building mounted situation is made from aluminium (a highly energy intensive material). Mast mounted turbines (predominantly in rural areas) are usually mounted on a type of scaffold pole or (less often) on a timber frame. A large scaffold pole (for a 10 m high

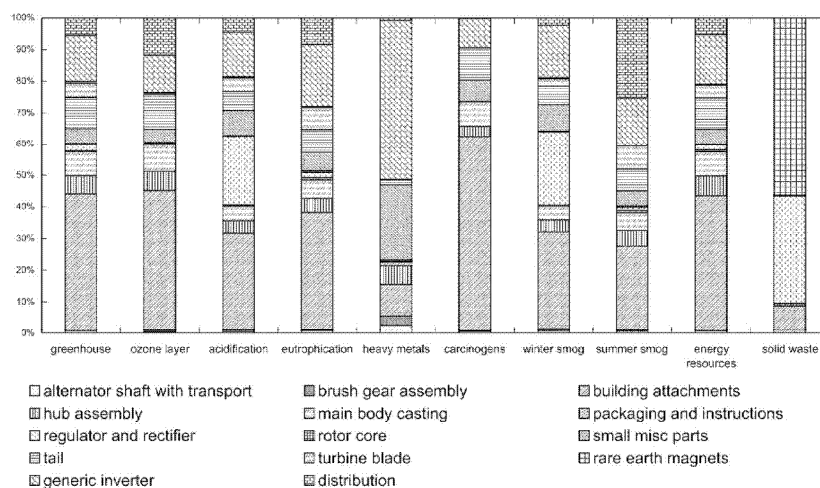


Fig. 8 Characterized microgenerator production data

turbine) has been calculated to have approximately the same embodied energy as a smaller (building mounted) aluminium pole. Other components with large impacts are the rare earth magnets, which have a large impact in terms of solid waste, and the inverter. Unfortunately, no detailed information has yet been found for the production of an inverter. However, it is known that the inverter used for this turbine is 16 kg and is covered in stainless steel. Using descriptions of the components given by electrical engineering colleagues at the University of Bath, it was presumed that the inverter contained a cast iron core and copper or aluminium wire. Therefore, these materials were used for the present study. No data for the disposal of the microgenerator have been included as there is little information about generator disposal available as it is still a relatively new technology.

The characterized data (Fig. 8) show the impact the materials have to each of the environmental issues considered within the study. It does not show the relative importance of the impact on any of these categories. In order to make a realistic comparison between the different environmental burdens, a process of normalization must be employed.

Figure 9 shows the normalized LCA data for material, processing, and transportation. It indicates that the impact towards heavy metals is by far the most significant, although it is worth noting that the actual values shown on the graph are small for all the environmental categories considered. Other comparatively significant impacts occur towards carcinogens and energy resources. The main contributor is the inverter

and the aggregated 'small and miscellaneous' parts. The latter has been further analysed in order to determine the reason for the impact on heavy metals. This analysis (see Fig. 10) shows that this impact is mainly a result of the aluminium, copper, and steel mining, smelting, and re-processing. Figure 10 indicates the characterized data of the components of the small and miscellaneous parts. The main contributions come from the stator laminators and the slip ring. The slip ring is very small, and when the data are examined once they have been normalized, it is shown that the only real impact is in terms of heavy metals. The stator laminations and the slip ring both contribute towards this; the impact being mainly from the steel and copper contained within the stator laminators and (again), the copper contained within the slip ring.

### 3.3 Micro-wind generator production and operation impacts

The energy output of the turbine was discussed previously and Fig. 5 depicts the calculated annual energy outputs in rural and urban areas. These results have been used within the LCA study to provide estimates of the environmental impacts associated with the life cycle of the microturbine.

Any energy produced by the turbine has been presumed to offset the primary energy that would have been required to deliver the same amount of electricity to the consumer with the current UK electricity

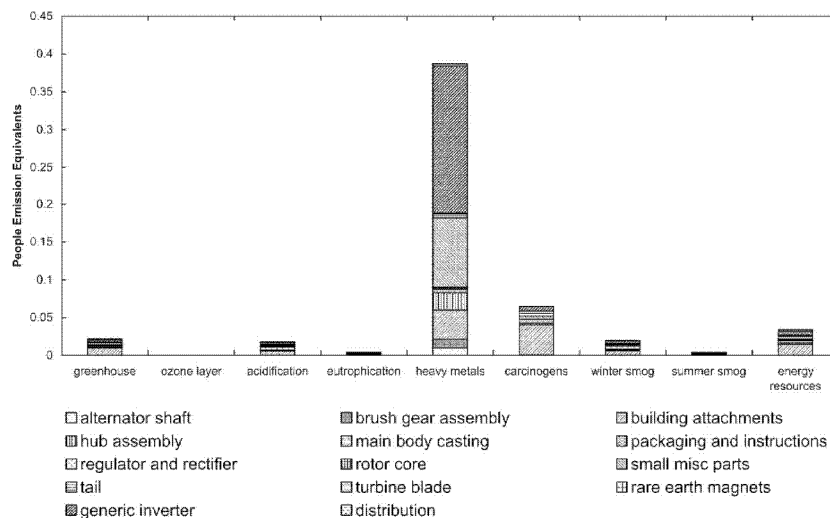


Fig. 9 Normalized microgenerator production data

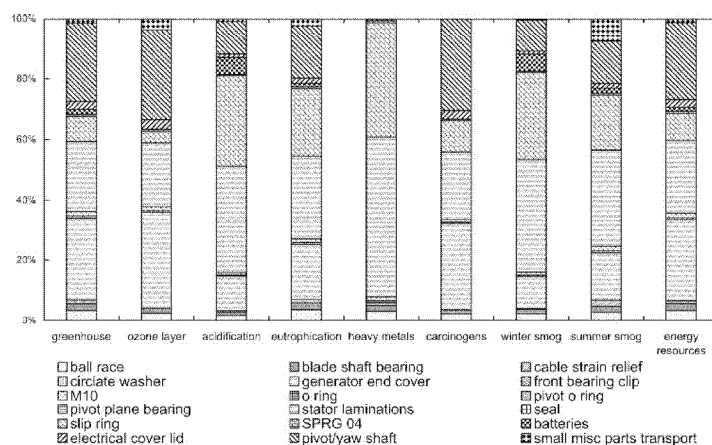


Fig. 10 Characterized 'small and miscellaneous' parts data

generation system. A specific grid 'energy mix', typical of the UK, has been established within the LCA software used. A comparison of the impact of turbine production compared with its energy output in urban areas is shown in Table 1. The data show that, in an urban environment, the turbine saves more GHGs than it consumes during production even with the minimum urban energy output over its 15 year life. This is also the case for energy resources. In the case of acidification, eutrophication, and winter and summer smog, the turbine has to achieve the mean urban energy output before the environmental burdens associated with its production are outweighed by its use in an urban setting. The impact of heavy metal pollution from the production of the micro-wind turbine is greater for the production than all but the maximum possible outputs for the turbine.

Table 2 shows the characterized data applicable to the open or rural environment. In all the categories, even the minimum energy output is sufficient to either offset or match that produced during the turbine production. The data in these tables illustrate the

impact of offsetting the equivalent amount of energy if it were delivered to the home from the grid. If the energy mix on the grid were to change, for example, if the fossil fuel inputs were reduced, it could have a significant impact on these results.

## 4 DISCUSSION

### 4.1 Turbine production

The LCA results for the turbine production show that the embodied energy, per kg, for the turbine studied is 143 MJ. This is similar to that found by Ancona and McVeigh [39], but much smaller than that found by Rankine *et al.* [40] who have undertaken a similar analysis for a Swift turbine with a calculated embodied energy of 240 MJ per kg. The difference is probably a result of a varying proportion of aluminium that is recycled for use within the turbines. A large percentage of the turbine components are made from aluminium and so any differences in the embodied energy values

Table 1 Characterized production data compared with energy output in urban areas over a 15 year lifetime

Impact category	Unit	Turbine production	Minimum urban energy output	Mean urban energy output	Maximum urban energy output
Greenhouse	kg CO <sub>2e</sub>	288	-536	-1420	-2670
Acidification	kg SO <sub>2</sub>	2.01	-2.05	-5.43	-10.2
Eutrophication	kg PO <sub>4</sub>	0.16	-0.13	-0.34	-0.64
Heavy metals	kg Pb	0.02	0.00	-0.01	-0.02
Winter smog	kg SPM	1.84	-1.54	-4.07	-7.68
Summer smog	kg C <sub>2</sub> H <sub>4</sub>	0.07	-0.04	-0.10	-0.18
Energy resources	MJ	5320	-10 200	-27 000	-51 000
Solid waste	kg	221	0.00	0.00	0.00

**Table 2** Characterized production data compared with the energy outputs in open areas over a 15 year lifetime

Impact category	Unit	Turbine production	Minimum open energy output	Mean open energy output	Maximum open energy output
Greenhouse	kg CO <sub>2e</sub>	288	-2380	-7520	-13 100
Acidification	kg SO <sub>2</sub>	2	-9	-28	-50
Eutrophication	kg PO <sub>4</sub>	0.16	-0.57	-1.81	-3.14
Heavy metals	kg Pb	0.02	-0.02	-0.07	-0.12
Winter smog	kg SPM	1.84	-6.86	-21.6	-37.6
Summer smog	kg C <sub>2</sub> H <sub>4</sub>	0.07	-0.16	-0.51	-0.88
Energy resources	MJ	5320	-45 500	-143 000	-249 000
Solid waste	kg	221	0.00	0.00	0.00

will have a dramatic effect on the resulting value for the energy used to produce the micro-wind generator. The Ecoinvent database used in the present study estimates that to produce 1 kg of virgin aluminium takes 201 MJ, but to produce 1 kg of recycled aluminium takes only 23 MJ. Rankine *et al.* [40] also found the aluminium components to be a significant factor in their energy analysis. They suggest a range of values for the energy content of aluminium to be 93–238 MJ, although the specific energy content selected to produce their energy production data is not given. In the present study, a percentage of recycled aluminium has been included in accordance with information gathered from the manufacturer.

As the amount of recycled aluminium has a significant impact on the energy used to produce the micro-wind turbine, a sensitivity analysis was conducted on the turbine considered in this research. By using virgin aluminium in all relevant parts of the generator, the energy used in production changes to 8220 MJ. This compares with 5320 MJ when using the recycled content adopted for this study (just over 50 per cent recycled, not including alloys or powder coatings). Using virgin aluminium for turbine production means that the amount of energy used to produce the turbine per kg increases to 224 MJ. Approximately 60 per cent of the aluminium used in the UK is recycled, and the turbines will be able to be recycled at the end of their life. Recycled aluminium cannot be used in all cases as there is typically very small contamination with other metals. However, this is not believed to be a problem with the majority of micro-wind turbine components.

#### 4.2 Turbine use

The LCA indicated that the micro-wind turbine has a positive environmental effect in all categories considered in all but the poorest wind conditions. The study compared the production of the turbine with the avoided impact of the use of grid electricity rather than using a more conventional energy payback method. This comparative analysis with grid electricity has a

significant impact on the results and therefore a further examination of the energy analysis is provided below.

#### 4.3 Energy analysis conventions

A variety of methods and conventions may be applied when undertaking an energy analysis and the chosen procedures should be both explicit and consistent with the aims of the study. Owing to this variation, it can be difficult to compare the results of different studies. The conventions and definitions applied within the present study are outlined below.

Electricity can be classed as either primary or secondary, depending on the generation method. Primary electricity generators include wind, solar, and hydro systems, generating electricity directly from the applicable resource. Secondary electricity is derived from a primary source, such as through the combustion of a fossil fuel.

The gross energy requirement (GER) is defined as the life cycle primary energy inputs required to deliver a good or service to the point of interest. In this case, the good/service is delivered energy in the form of electricity, and the GER is thus defined by

$$\text{GER} = \frac{\text{Life cycle primary energy input (MJ)}}{\text{Lifetime delivered energy (MJ)}} \quad (6)$$

Thus, wherever derived energy resources, such as secondary electricity, are used as an input they must be accounted for in terms of their primary energy requirement, in order to give the complete picture of energy required to produce and sustain the system. For example, the GER of electricity generated in a coal-fired power station would include the primary energy value of the coal combusted. This differs from the net energy requirement (NER), which does not include the energy content of the original source of energy [41, 42]. The NER and/or indicators based upon this value have been presented in previous studies of electricity generators [42–44].

The energy gain ratio (EGR) and energy payback period (EPP) are further metrics that can be used to

assess electricity generation technologies. The EGR is defined as the energy output from a generator over its lifetime divided by the life cycle primary energy input, and is therefore the inverse of the GER or NER (depending on the conventions employed in a particular study). The EPP is analogous to a financial payback period (often termed 'break-even point'), and represents the number of years that a system must operate until its energy output equals the life cycle primary energy input. The convention employed in this study is to include transmission and distribution losses, thus comparing systems on a delivered energy basis.

#### 4.4 Energy analysis results

Table 3 summarizes the GERs and equivalent EGRs (based on the GER) for a variety of electricity generation technologies. It shows that, for a given primary energy investment, renewable generators provide a greater electricity output over their lifetime by approximately one or even two orders of magnitude. Some of the thermal power stations can be suitable for CHP production, which would increase their corresponding EGR. It is important to note that, although Table 3

provides information enabling a comparison of technologies on energy terms, there are a variety of other issues that must also be considered. Capacity credit and geographical suitability, along with flexibility of plant and other ancillary services, are among the range of aspects that require attention [45]. Energy analysis therefore provides data that can form part of an interdisciplinary toolkit for energy system assessment [15].

When considering an investment of primary energy for electricity generation, options include sustaining the current system or producing and maintaining a new generator. During assessment of the energy and environmental impact of installing a new generator, performance may therefore judged by comparison with the current system. This concept has previously been described as the opportunity cost convention [46, 47]. Its precursor is the similar economic convention, which would consider the performance of one financial investment in comparison with another.

The mean urban microturbine generates 590 MJ (164 kWh) of electricity locally per year, as shown in Fig. 5. Assuming this output is consistent over its lifetime, the corresponding standard EGR is  $1.7 \text{ MJ}_{\text{delivered}}/\text{MJ}_{\text{primary}}$  (Table 3). This study shows that the current UK grid consumes approximately 1800 MJ

**Table 3** Gross energy requirements of electricity generation technologies

Electricity generation technology	GER	EGR	Comments
	( $\text{MJ}_{\text{primary}}/\text{MJ}_{\text{delivered}}$ )	( $\text{MJ}_{\text{delivered}}/\text{MJ}_{\text{primary}}$ )	
Current UK grid <sup>a,b</sup>	3.1	0.33	Representative of the current UK electricity system
Coal <sup>b</sup>	3.5	0.29	Representative of electricity production from coal in Union for the Co-ordination of Production and Transmission of Electricity countries
Natural gas <sup>b</sup>	2.3	0.43	Based on average of natural gas power plants in Great Britain
Oil <sup>b</sup>	4.6	0.22	Based on UK specific efficiency of transformation. Assumed mix of 35 per cent combined cycle plants (1.9 TWh), 65 per cent from power plants (3.6 TWh)
Nuclear <sup>b,*</sup>	3.5	0.28	Represents the average European nuclear mix of 90 per cent pressurized water reactors and 10 per cent boiling water reactors (values based on electricity delivered 1995–1999)
Hydro <sup>b</sup>	0.01	93	Based on the UK share of run-of-river and reservoir hydro schemes
Wind (2 MW offshore) <sup>b</sup>	0.06	16	Based on a capacity factor of 30 per cent
Wind (800 kW onshore) <sup>b</sup>	0.05	19	Based on a capacity factor of 20 per cent. Values may therefore be conservative; the average UK capacity factor (1998–2004) was 29 per cent (DTI [49]).
Solar (3 kW <sub>p</sub> roof mounted) <sup>b</sup>	0.34	2.9	Values may be optimistic. They are based on the solar resource available in Switzerland, which is approximately 1300–1600 kWh/m <sup>2</sup> , compared with the UK's resource of 900–1300 kWh/m <sup>2</sup> (European Communities [50])
'Mean open' micro wind (600 W) <sup>c</sup>	0.11	8.8	Based on a capacity factor of 17 per cent (870 kWh annual output)
'Mean urban' micro wind (600 W) <sup>c</sup>	0.60	1.7	Based on a capacity factor of 3 per cent (164 kWh annual output)
Comparative micro-wind turbine (600 W) <sup>d</sup>	0.26	3.9	Based on a capacity factor of 23 per cent (1200 kWh annual output)

Source: <sup>a</sup>Adapted from reference [10]; <sup>b</sup>reference [38]; <sup>c</sup>present study; <sup>d</sup>reference [39].

\*Note that the spent fuel of a nuclear reactor may contain, with reprocessing, utilizable energy.

in order to produce the same quantity of 590 MJ delivered electricity, which corresponds to an EGR of  $0.33 \text{ MJ}_{\text{delivered}}/\text{MJ}_{\text{primary}}$ . The mean urban turbine would therefore produce approximately 5.2 times more electricity than the current UK grid currently produces, per unit of invested primary energy. This value will henceforth be referred to as the 'displaced EGR'. The standard EPP of the mean urban turbine is 9 years, but when considering the quantity of primary energy displaced from the grid, the 'displaced EPP' is reduced to 3 years. As the mix of generation technologies comprising the grid changes, the displaced gain ratios and payback periods will change accordingly. Standard and displaced EGRs and EPPs are presented for the micro-wind turbine in Figs. 11 and 12, respectively, and show how the performance varies with annual electricity production. The gain ratios and payback periods of other renewable technologies will

also change considerably when the displaced primary energy of the current grid is considered, although large centralized generation technologies will suffer transmission and distribution losses to the point of delivery (these are approximately 7.5 per cent, [2]).

#### 4.5 Electricity as an energy carrier

The energy analysis metrics produced thus far apply to system boundaries that encompass the energy and material resources in the ground, and extend to the point of electricity delivery. When determining the most appropriate mix of energy generation technologies for a whole economy, the boundaries must be extended to include the 'end-use' [13] of energy, for the following reasons.

Electricity may be regarded as an energy carrier having a high quality, or exergy, because it can provide either power or heat. In contrast, low temperature hot water can only be used for heating purposes and is therefore of lower quality. In an electricity sector dominated by depleting (fossil and nuclear) fuel resource inputs, it is important to utilize energy resources with the greatest 'full fuel cycle' efficiency. This implies using electricity for high-quality applications only, rather than for low-quality heat supply. When providing heat, primary energy consumption is more efficient if fuels are burnt directly. In practice, electricity is often used for cooking process, heating, and for space or water heating [5, 11, 43].

Depleting energy resources have been described as 'capital' resources that were laid down, or invested, over geological timescales. These can be contrasted with 'income', or continuously renewable, resources. Should the UK energy sector switch to zero or low carbon generators from (say) the middle of this century,

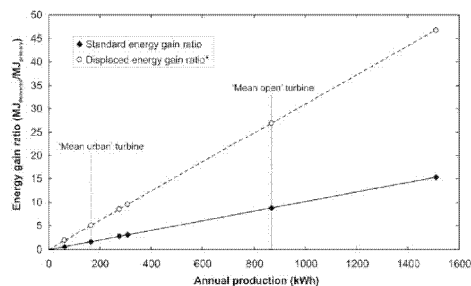


Fig. 11 Turbine EGR for varying annual electricity production. \* Note that the displaced EGR compares the standard EGR with the EGR of the current grid, and is therefore dimensionless

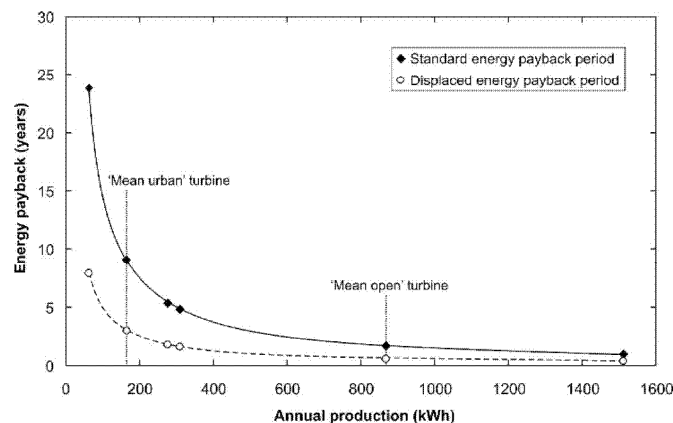


Fig. 12 Turbine EPP for varying annual electricity production

then that would imply the use of renewable inputs, which are an essentially free resource. Under those circumstances, the efficiency of energy utilization could become a less important end-use consideration. Whether that happens will depend on a balance between the likely rise in the long-term price of fossil fuels and the capital costs of the equipment needed to utilize renewable energy sources. Presently, the economics of some of the domestic microgenerators do not look attractive in the UK context; see, for example, Butcher *et al.* [48]. However, that is expected to change over the medium-term (see Allen *et al.* [5]).

## 5 CONCLUDING REMARKS

This study has examined the life cycle of a micro-wind turbine, based on the assumption that the electricity used will displace power from the grid. The results show that the environmental impact and benefit of the micro-wind turbine is dependant on a number of factors, primarily the geographical positioning of the turbine, the available wind resource, and whether or not recycled materials (mostly aluminium) are used to construct the generator.

Energy output estimations were made for a micro-wind turbine with a diameter of 1.7 m and rating of 600 W at 12 m/s. For a selection of urban environments, the estimated annual outputs had a mean of 160 kWh (range: 60–310 kWh). In open environments, this figure increased to 870 kWh (range: 280–1500 kWh). The positioning of the turbine will therefore affect the energy output significantly. Power output is proportional to the cube of the wind speed, and wind speed increases with height from surface roughness while turbulent effects decrease. Consequently, mounting height influences the energy yield significantly, and it is clear that situating the turbine as high as possible, and clear of wind shadowing and surface roughness, is of great importance. The estimation methodology, based on hourly average wind speeds and a simple turbulence intensity related estimation adjustment, requires validation, particularly in the case of the urban environment. The results of ongoing micro-wind turbine field trials, due to report in 2008, will be a valuable first step toward this end.

The UK average household electricity consumption was approximately 4500 kWh over the period 2000–2005, which shows that energy efficiency and demand reduction measures are vital alongside the installation of a micro-wind turbine, if such devices are to contribute significantly to demand. Current market conditions in the UK do not favour microgenerators. However, even under more favourable conditions, the financial feasibility will be significantly affected by the proportion of demand that can be met by the micro-wind turbine.

The EGRs presented in this study indicate that for a given primary energy investment, the electricity delivered by the turbine is an order of magnitude larger than for fossil or nuclear-based generation technologies. When the electricity generated by the turbine is valued as the quantity of primary energy that is displaced from the current grid, the gain ratios increase by a factor of approximately 3. These displaced gain ratios give the performance of the turbine in relation to the current electricity network (i.e. how many times more electricity is generated per unit of primary energy input). The standard EPP is 9 years in the mean urban case, whereas the displaced EPP is approximately 3 years. For the mean open (i.e. rural) case, the standard and displaced paybacks are 1.6 and 0.6 years, respectively. When the mix of generation technologies comprising the UK electricity network changes in the future (primary versus secondary power technologies), the displaced gain ratios and payback periods will change accordingly.

The production of the turbine has been shown to give rise to heavy metal pollution which is mainly as a result of the use of aluminium, copper, and steel via smelting and re-processing. However, this impact is not considered to be significant on a global scale and it has positive impacts if used in an open or rural environment, or if the maximum output is achieved in an urban environment. An increased use of recycled aluminium in turbine manufacture would reduce the negative impact even further.

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The authors' names appear alphabetically.



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## APPENDIX

## Notation

$A$	area
BAWT	building augmented wind turbines
BWEA	British Wind Energy Association
DCLG	Department for Communities and Local Government
DEFRA	Department for Environment, Food and Rural Affairs
DTI	Department of Trade and Industry (renamed as the Department for Business Enterprise and Regulatory Reform (BERR) in June 2007)
$I$	turbulence intensity
ISO	International Organization for Standardization
K.E.	kinetic energy
$m$	mass
$\dot{m}$	mass flowrate
ML	mixed layer
$P$	power
SETAC	Society of Environmental Toxicology and Chemistry
$u, v, w$	perpendicular velocity components
UCL	urban canopy layer
VAWT	vertical-axis wind turbines
$\rho$	density
<i>Subscripts</i>	
$e$	electricity (used to define power as electrical)
$G$	gross (referring to the gross power available in the wind)
<i>Superscripts</i>	
$\cdot$	first derivative with respect to time
$-$	time-mean
$'$	fluctuating component about the mean
$\wedge$	root mean square



# Prospects for and barriers to domestic micro-generation: A United Kingdom perspective

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## Abstract

Approximately 38% of current UK greenhouse gas emissions can be attributed to the energy supply sector. Losses in the current electricity supply system amount to around 65% of the primary energy input, mainly due to heat wasted during centralised production. Micro-generation and other decentralised technologies have the potential to dramatically reduce these losses because, when fossil fuels are used, the heat generated by localised electricity production can be captured and utilised for space and water heating. Heat and electricity can also be produced locally by renewable sources. Prospects and barriers to domestic micro-generation in the UK are outlined, with reference to the process of technological innovation, energy policy options, and the current status of the micro-generation industry. Requirements for the main technology options, typical energy outputs, costs to consumers, and numbers of installed systems are given where data is available. It is concluded that while micro-generation has the potential to contribute favourably to energy supply, there remain substantial barriers to a significant rise in the use of micro-generation in the UK.

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**Keywords:** Distributed generation; Micro-generation; Low and zero carbon technologies (LZC); Innovation; Market barriers; Policy drivers

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## 1. Introduction

### 1.1. Background

Changes in atmospheric concentrations of greenhouse gases (GHGs) affect the energy balance of the global climate system. The effect of human activities on these concentrations and the resulting anthropogenic climate change have been disputed and controversial topic in recent years, and had become increasingly prevalent in public awareness and discourse. The 2007 Intergovernmental Panel on Climate Change (IPCC) scientific assessment stated with ‘very high confidence’ that humans are having an effect on the climate [1]. In order to mitigate against significant anthropogenic alterations in climate, the Royal Commission on Environmental Pollution in the UK recommended a 60% cut in UK CO<sub>2</sub> emissions by 2050 [2]. This has recently been adopted as a legally binding target by the UK Government [3]. The Tyndall Centre for Climate Change Research has

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**Abbreviations and nomenclature**

BAWT	building augmented wind turbine
CCL	Climate Change Levy
CERT	Carbon Emissions Reduction Target
CHP	combined heat and power
CoP	co-efficient of performance
DTI	Department of Trade and Industry (renamed as the Department for Business Enterprise and Regulatory Reform (BERR) in June 2007)
EEC	Energy Efficiency Commitment
EST	Energy Saving Trust
EWP	Energy White Paper
GHG	greenhouse gases
GSHP	ground source heat pump
HAWT	horizontal axis wind turbines
IPCC	Intergovernmental Panel on Climate Change
LCBP	Low Carbon Buildings Program
LPG	liquid petroleum gas
OFGEM	Office of Gas and Electricity Markets
PV	photovoltaics
RO	Renewables Obligation
ROC	Renewables Obligation Certificates
VAWT	vertical axis wind turbine

*Subscripts*

e	electrical
th	thermal

called for more significant reductions of 70% by 2030 and 90% by 2050 [4], highlighting that the steepest reductions in emissions must occur between now and 2030.

Alongside the issue of climate change are those of fossil fuel dependence, energy security and energy costs. Energy demand worldwide is growing, and finite fossil fuel supplies are able to provide for this demand for a limited time. However, there is considerable uncertainty over fossil fuel resources in the mid to long term [5], which will affect energy security and relative energy costs.

Against this global backdrop, the UK Government has four long-term goals for energy policy [6]:

- To put the UK on a path to cut carbon dioxide emissions by some 60% by about 2050, with real progress by 2020.
- To maintain reliable energy supplies
- To promote competitive markets in the UK
- To ensure that every home is adequately and affordably heated.

Micro-generation could be an effective mechanism to help achieve these targets and its use is being promoted by the UK Government. However, there are problems associated with some of the micro-generation technologies and the ways in which they are funded and encouraged. These issues will be examined in this paper.

### *1.2. Distributed energy and micro-generation*

The current electricity supply system of the UK is highly centralised, and relies heavily on the combustion of fossil fuels that produce pollutants including climate-changing GHGs. In 2004 energy industries (these

include electricity generation, the use of fossil fuels for petroleum refining, and the production of coke and solid smokeless fuels) was the biggest single contributing category to the UK's CO<sub>2</sub> emissions, being responsible for about 58MtC or 38% of net CO<sub>2</sub> emissions [7]. Most supplied electricity is generated by large thermal power plants that connect to a high-voltage transmission network, to be transmitted and then distributed to end-users via regional low-voltage distribution networks. This centralised model has delivered economies of scale and reliability but there are significant drawbacks. For example, the electricity supply system suffers an approximate loss of 65% of the primary energy input [8], predominantly as a result of heat wasted during electricity production, but also through transmission and distribution losses. Clearly, thermodynamic constraints prevent elimination of these losses completely; however decentralised technologies such as combined heat and power (CHP) plants can dramatically increase the efficiency of fossil fuel use by capturing some of the rejected heat and supplying it for space and water heating. Heat and electricity can also be produced locally by renewable sources such as solar thermal systems and micro-wind turbines.

*Decentralised or distributed* energy supply refers to the generation of energy close to the point of use. It can denote a range of generator sizes; from community or district-level down to individual households. *Micro-generation* is defined in Section 82 of the Energy Act (2004) as “the small-scale production of heat and/or electricity from a low carbon source” [6]. It has further been defined as anything below 50–100 kW, with most household electricity-supply installations being below 3 kW<sub>e</sub>; slightly larger for heat-supply [9]. It has recently been predicted that micro-generation could provide 30–40% of the UK's electricity needs by 2050 [9].

There are small pockets within the UK that are already taking steps toward a more distributed energy system. Woking Borough Council, for example, achieved a 49% reduction in energy consumption and a 77% reduction in CO<sub>2</sub> emissions between 1991 and 2004. Woking invested the profits in renewable energy projects, and by 2004 had installed 10% of the UK's solar photovoltaic (PV) capacity and the UK's first fuel-cell combined heat and power (CHP) system (200 kW<sub>e</sub>). It has a network of 60 local generators, including CHP to heat and cool municipal buildings, social housing and town-centre businesses [6,10].

Kirklees Council in West Yorkshire now accounts for 5% of the UK's installed solar PV capacity and has fitted over 160 houses with solar thermal water-heating systems along with supporting community micro-wind installations on both a local sports college and community centre. Seventy-nine energy efficient homes have been created, with owners installing solar PV or micro-wind turbines [6].

Other EU countries are proving that decentralised energy systems are feasible. Malmö in Sweden, for example, matches demand with localised supply from 100% renewables (on an annual basis). A 2 MW wind turbine, solar PV, heat pumps and solar thermal systems supply heat and electricity. Excess energy is exported, and imports are possible when there is a shortfall. Over a year, supply is designed to balance demand.

Decentralised supply and micro-generation are, however, yet to have a significant impact on the UK's energy system. There are currently fewer than 100,000 micro-generation installations (most of which are pre-2000 solar thermal systems), which represent only 0.5% of the UK's electricity supply [6,9]. All combined heat and power plants amount to only 7% of the total supply.

Decentralised energy supply is site specific in relation to both the energy resource and energy demand. Micro-generation can be suitable for the domestic sector, and also has some public and commercial sector applications (e.g. community centres and businesses). This paper will concentrate on domestic supply and demand.

## 2. Technological innovation and energy policy

### 2.1. Innovation systems

There is a large body of literature concerning innovation that includes recent emphasis upon the energy sector. The micro-generation industry, similar to the development of any technology, can be viewed from the perspective of innovation theory. An *innovation system* may be defined as “the elements and relationships which interact in the production, diffusion and use of new, and economically-useful, knowledge” [11]. Foxon et al. [11] provides a useful simplified representation (Fig. 1) of the process of innovation, which includes the various actors and institutions and the relationships between them.

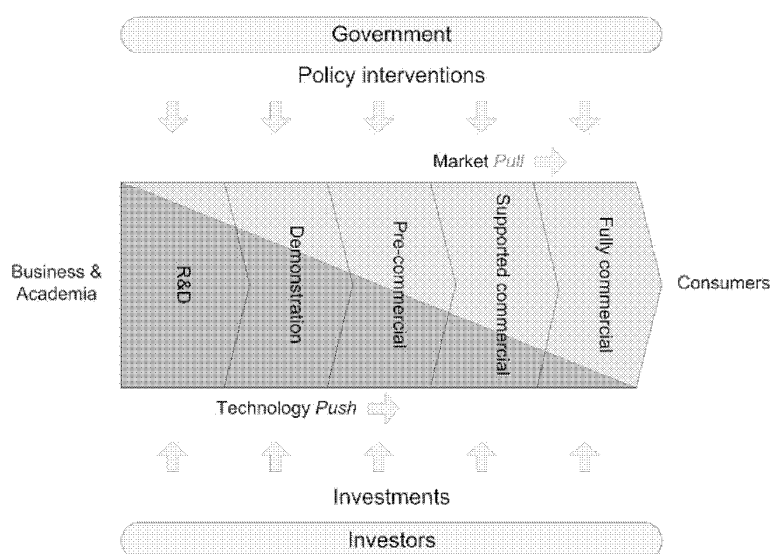


Fig. 1. Roles of innovation chain actors (adapted from [11]).

While Fig. 1 implies a linear process (from basic R&D to diffusion of a commercial technology), it is important to emphasise that in fact innovation is a dynamic, non-linear process; a concept supported by Foxon et al. [11]. Thus the final picture is more complex, as feedback loops exist between the different stages and there are important links between technological and institutional change that require consideration. A whole-system perspective of the innovation process is therefore appropriate (as opposed to considering each stage in isolation), and it is from such a perspective that policy guidance should be drawn.

## 2.2. Innovation and energy policy

The market penetration of a (successful) new technology typically varies in the manner of the hypothetical S-shape curve shown in Fig. 2. Take-up of the technology begins slowly, then as commercial viability is reached production ‘takes off’ and the technology rapidly diffuses before gradually slowing down as the market saturates. Correspondingly, the cost of production of a technology tends to reduce as production volumes increase; a phenomenon reflected by ‘experience curves’ (also known as *technology-learning curves*). Fig. 3 corroborates this concept, showing experience curves for a variety of electricity-generating technologies in the EU [12]. The causes of cost reduction vary, but can include learning-based improvements and economies of scale. It is clear therefore that higher costs for new technologies present a barrier to entry when competing with established technologies. This contributes to the ‘lock-in’ of incumbent technologies, and highlights the path dependence of development; both of which can discourage innovation. In order to promote innovation and create a market of diverse technology options, these processes must be considered in the context of policy-making.

The appropriate policy instruments will vary with the stage of a technology’s development. The dynamic nature of innovation suggests that each instrument will influence the market interactively and thereby the effectiveness of other policies. Some prevalent energy policy strategies are indicated in Fig. 2, and will be discussed below in the context of the UK micro-generation industry. The various types of market intervention are as follows:

*R&D support* includes research programmes and grants encouraging public, academic and private R&D, tax credits and ensuring a supply of trained scientists. Over the period 1974–2004 there was a significant downward trend in both public and private R&D expenditure in OECD countries, which correlates broadly with oil price trends [13]. The UK Government’s Stern Report [14] of the economics of climate change called for a

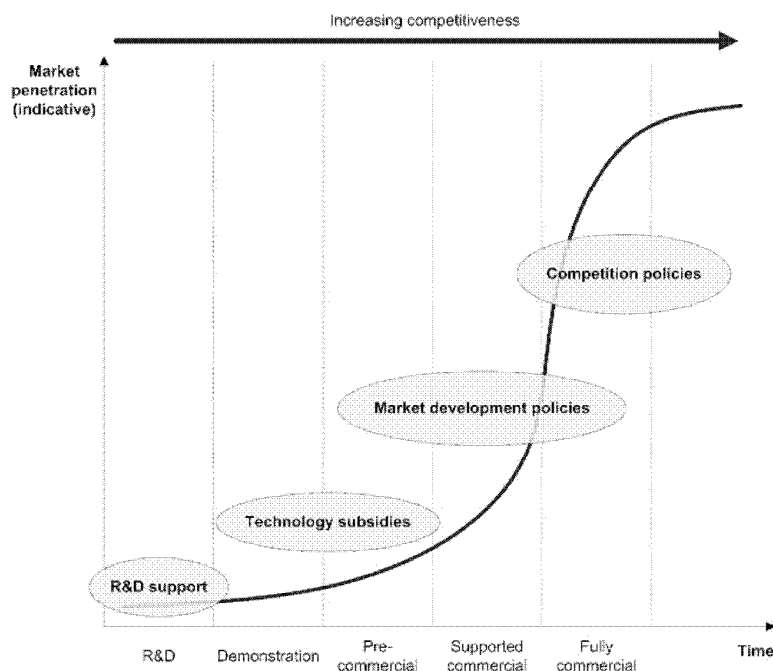


Fig. 2. S-curve of technology development and policy categories (adapted from [11,16]).

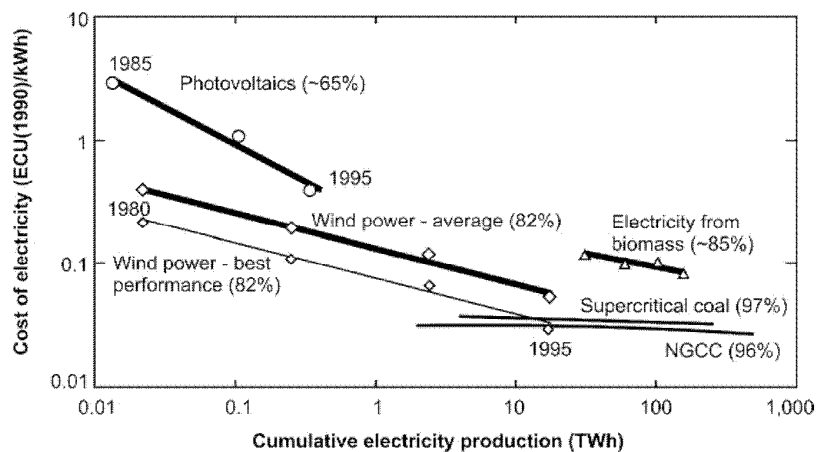


Fig. 3. Experience curves for electricity-generation technologies in the EU, 1980–1995 (Source: [12]).

doubling of global public energy-R&D funding (to around \$20 billion annually) for the development of a diverse portfolio of technologies, which represents a drastic increase compared to past decades (of around \$10 billion annually).

*Technology subsidies* include demonstration project funding and support for early-stage commercialisation. Examples in the UK relating to micro-generation include the UK Department of Trade and Industry's (DTI) previous subsidy programmes: the Clear Skies and Photovoltaic Demonstration Programmes and the current Low Carbon Buildings Programme will be discussed later in this paper. The Stern Report [14] advocates a two

to five-fold increase in deployment incentives from current levels of around \$33 billion (in addition to a carbon-price).

*Market development policies* include feed-in tariffs, specialised auctions, tax credits, accelerated depreciation and the creation of niche markets. Under these policies new technologies can develop with a degree of protection from the mainstream energy markets; permitting simultaneous development of a range of technologies. Countries such as Germany, Denmark and Spain have achieved substantial growth in renewable energy technologies, including wind power and solar PV, via feed-in tariffs (long-term policies in which a guaranteed fixed price for electricity typically reduces over time). The USA has a large installed capacity for renewables encouraged by other means, such as tax credits and accelerated depreciation [15]. Moving in the direction of increasing competition are niche market policies, such as tradable certificates. The market is then left to determine the price of certificates, which can lead to price uncertainty (and increased risk to investors), but also promote cost-efficient solutions. Niche markets can exist at different levels; for example a higher level, inter-technology market for renewable electricity, or a niche market for a specific technology. Inter-technology certificate markets risk encouraging technological lock-in of the short-term cost-efficient technology. Therefore if diversity of supply is required niche markets for specific technologies are more appropriate, as they are protected from alternatives during development.

Oxera [15], a UK energy consultancy, recently studied support policies for renewables in seven countries (Australia, Denmark, Finland, Germany, Italy, Spain, the UK and the USA). All countries deemed financial support for renewables necessary and, while the dominant mechanism has been feed-in tariffs, there is a trend towards certificate markets. Based on the EU research project 'REALISE', Midttun and Gautesen [16] argue that feed-in tariffs and certificate markets should not be seen as competing alternatives, but rather as complementary policy-steps in the technology development cycle outlined in Fig. 2.

*Competition policies* are appropriate for technologies approaching maturity, and include higher level certificate markets, third party access policies and corporate governance policies [16]. The aim is to create support that is sufficient for furthering commercialisation of technologies towards full competitiveness in the mainstream energy market, whilst providing cost-effective energy to consumers. The current Renewables Obligation in the UK is an example of an inter-technology certificate market, and will be discussed below.

A diverse range of energy policy instruments are in existence to support the UK Government's aim of securing clean, diverse, and cost-effective energy supplies. There can be tensions between such objectives; for example short-term cost-efficiency may conflict with diversity of supply. Whatever the chosen approach, recent literature [11,14,17] highlights the paramount importance of a stable, consistent, long-term framework from governments. Political aspirations are not seen as sufficiently 'bankable' by industry, and the policy therefore needs to be designed to send clear, investment-inducing signals to business, such as firm targets for renewables far out into the future. Policies should also have a clear review process and exit strategies for fully competitive technologies [14], further reducing risk for investors.

Closer collaboration between government and industry is called for in the Stern Report [14], and the development of a shared vision between government, industry and research community is of vital importance [11].

The Stern Report also advocates a realistic carbon price as a vital part of future policy; indeed, it argues that failure to take account of environmental externalities (such as climate change) ensures that there will be under provision and slower innovation [14]. However, carbon pricing is still in its infancy, and even where it is implemented uncertainties remain about the durability of the price signals over the long term. Regulation and alternative policy approaches (such as some of those mentioned above) are therefore vital to promote the required investment in sustainable technology innovation.

### 3. Domestic demand and distributed energy supply

#### 3.1. The UK market situation

Domestic energy demand across the UK varies per household for a range of reasons including household type; appliance use; number of occupants; behavioural patterns; energy source options and so on. To produce estimates of energy use for an average UK household, national domestic energy use separated by end-use and fuel type can be combined with UK household numbers [18,19], and is presented in Fig. 4.



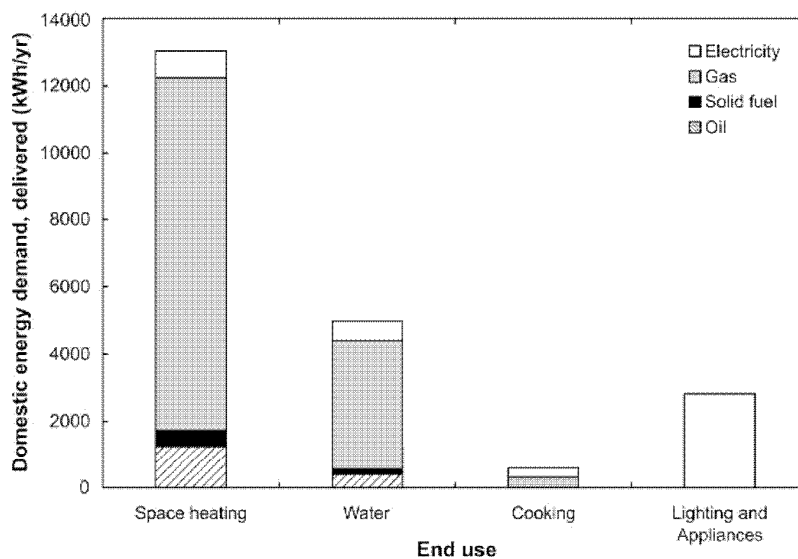


Fig. 4. Average 2002 UK domestic energy consumption per household by end-use and fuel type (Source: [18,19]).

The total end-use energy demand per average household is approximately 21,000 kWh/yr, which is supplied primarily by gas and electricity (70% and 21%, respectively). 61% of this demand is space heating; 23% water heating; 3% cooking and 13% lighting and appliances. Fig. 4 indicates that space and water heating are supplied primarily by gas; cooking by an approximately even mix between gas and electricity; while lighting and appliances are supplied entirely by electricity.

When considering the impact of energy use it is important to consider the *primary energy* consumed alongside *end-use* demand. In the case of electricity for example, only 35% of the energy input to power stations is delivered as electricity to the end user [8]. Therefore 1 unit of energy consumed in the household represents approximately 2.9 units of primary energy input into the power station. It is vital that this is considered when assessing the benefits of installing a micro-generator: it is the primary energy that needs to be offset rather than just the end-use energy.

Micro-generation technologies have the potential to supply energy for domestic consumption locally. Different technologies will satisfy different end-use demands, with corresponding carbon and financial saving potentials that depend on the carbon intensity and the cost of alternative supply options respectively. Demand reduction and energy efficiency measures are highly recommended alongside any micro-generation installation; indeed to gain access to UK Government grants (Low Carbon Buildings Programme) efficiency measures must be implemented. Such measures are likely to reduce demand from the average UK household represented in Fig. 4.

### 3.2. Solar thermal

Requirements in the UK for installation of solar thermal (water-heating) systems include a south-east to south-west facing roof space with minimal shading for most of the day; appropriate roof strength; and (in some cases) space for an additional water cylinder. The solar resource is well understood and relatively predictable on a seasonal basis. Typically all the energy produced is consumed onsite: the UK's Energy Saving Trust (EST) states that appropriate installations can provide almost all domestic hot water demand during summer months and an annual average of approximately 33% [20]. A side-by-side test of eight available systems reported estimated annual outputs of a mean of 1,145 kWh/yr and a range 954–1339 kWh/yr [21]. Comparing these values with Fig. 4 indicates agreement with the Energy Saving Trust figure of 33%, when typical boiler efficiencies are taken into account.

Solar thermal is currently the largest and most established micro-generation industry, with approximately 78,000 installations and an annual installation rate of 2000 units [9]. There are many different systems available, with a variety of plumbing options, but, in general, capital costs for typical 4 m<sup>2</sup> systems are between £2000 and £3000 for flat-plate collectors and between £3500 and £4500 for evacuated tube systems [20].

### 3.3. *Solar PV*

Solar PV installation requirements are similar to those for solar thermal. The energy that a solar device can provide in any given period is known as the ‘solar fraction’. In the case of PV it does not distinguish between electricity that is consumed onsite and that which is exported, to be replaced by imports later. A recent field trial covering 15 sites, representing 230 systems and 382 individual values, found that for the average system size of 1.6 kW<sub>p</sub> a solar fraction of 51% was supplied [22].

There are currently 1300 solar PV installations across the UK; with about 500 more projects allocated under the Low Carbon Buildings Programme (see section below). In many cases, electricity supply and demand profiles will not match, and hence the economics of exporting and importing will have a large effect on the financial feasibility of a grid-tied PV installation. Typical domestic installations cost around £4000 to £9000 per kW<sub>p</sub> installed [23].

### 3.4. *Micro-wind*

There are three broad categories of small-scale wind turbine available: horizontal-axis wind turbines (HAWTs); vertical-axis wind turbines (VAWTs); and building augmented wind turbines (BAWTs). The latter category further breaks down into three sub-categories: turbines situated on a building; turbines placed in a duct through a building; and turbines located between diffuser shaped buildings [24]. Micro-wind turbines for domestic energy generation are a currently emerging technology in the UK marketplace, and as such there is relatively little empirical knowledge concerning their performance and corresponding energy yield potential, particularly in grid-tied situations and/or in the built environment. The wind resource is highly site specific and less predictable than the solar resource.

Bahaj et al. [25] suggest that for open areas with appropriate wind conditions, and with suitable mounting heights, there is potential for micro-wind turbines to make significant impact on domestic energy generation. Micro-HAWTs with roof-mounting options have recently become available, but there is doubt, fuelled by the current lack of empirical proof, of their suitability for roof-mounting particularly in urban environments. There are suggestions within the technical literature that micro-HAWTs are in fact unsuitable for urban environments in general, due to the complexity of the wind distribution [25,26]. Mertens et al. [24] concludes that certain VAWTs are preferable to HAWTs for roof-mounting upon (high) buildings. VAWTs do not suffer as much from reduced energy outputs as a result of frequent wind direction changes, whereas HAWTs must yaw and track the wind to be able to extract energy economically.

Field trials are underway to help assess micro-wind’s potential contribution to domestic energy-supply, the results of which will be publicly accessible [27,28]. There are currently 650 micro-wind installations across the UK, with around 1500 more projects allocated under the Low Carbon Buildings Programme. As with PV, electricity supply and demand profiles may not match, and hence the financial feasibility of grid-tied micro-wind installations will be significantly affected by export/import economics. Currently available systems of approximately 1 kW rated power will cost around £3000, whereas those in the range 1.5–6 kW cost between £4000 and £18,000 [29].

### 3.5. *Ground-source heat-pumps*

A few metres below the ground the temperature across the UK is a reliable 11–12 °C throughout the year, which is a sufficient heat source for a ground-source heat-pump (GSHP). The primary requirement is space to install a ground loop. It is possible to use radiators for heat distribution, but under-floor heating is preferable because it works more effectively at lower temperatures (30–35 °C). Systems can be designed to meet 100% of space-heating requirements, and in some cases can pre-heat domestic hot water. A heat pump requires elec-

tricity to drive system components in order to supply heat. The ratio of electricity required to heat supplied is known as the coefficient of performance (CoP). Typical CoPs range between 2.5 and 4; the higher end relating to systems with under-floor heating [30]. Retrofitting GSHPs can therefore be problematic; the best performance can require significant changes to the heat distribution system.

There are currently around 550 GSHPs installed in the UK, with 270 more projects allocated under the Low Carbon Buildings Programme. The consistency and reliability of the heat supply means that the financial feasibility of GSHPs is left primarily to the capital costs (which depend on the property and heat distribution system requirements), and alternative fuel costs. GSHPs can be viable investments now, when compared with electric or LPG heating, and the associated CO<sub>2</sub> savings are also high in these cases [9]. Typical 8 kW systems cost between £8000 and £12,000 plus the cost of the heat distribution system [30].

### 3.6. *Micro-CHP*

By utilising the heat produced during electricity production, CHP can operate at significantly higher efficiencies than traditional thermal power plants. Suitable prime-movers for micro-CHP include internal combustion engines, Stirling engines and fuel cells, which have varying heat-to-electricity generating ratios. Internal combustion engines generate noise and vibrations making them generally unsuitable for domestic application [31]. Stirling engines have a higher heat to power generating ratio than fuel cells, and are therefore more applicable to larger dwellings with higher heat loads in order to concurrently satisfy electricity demand. Fuel cells, on the other hand, are currently more suited to smaller dwellings with lower than average heating demands [9].

An ongoing field-trial has reported poorer than expected efficiencies for ~1 kW<sub>e</sub> micro-CHP units [32]. This has been the result of the relatively high thermal inertia associated with the units, in combination with intermittent heat demand that drives their operation. A micro-CHP unit must be operating at a fairly high temperature before it can generate electricity. During its warm-up period, it will provide some heat, but no electricity. Energy is absorbed while warming up the mass of the unit to operating temperature, of which little can be usefully recovered. Small-scale CHP for business (up to approx 25 kW<sub>e</sub>) has fared better in the trial, as the typical operating conditions were steady state and so warm-up losses were negligible. Modern boilers with a lower thermal mass may therefore be more appropriate than micro-CHP, especially for domestic use with typically more intermittent heat demands, in terms of energy efficiency and the resulting carbon performance [32]. The field trial is due to publish its final report in late 2007.

There are currently 990 micro-CHP units installed in the UK. The Whispergen micro-CHP unit is an available Stirling-engine technology, sized for domestic application (1 kW<sub>e</sub>, 7→12 kW<sub>th</sub>), and costs approximately £3000 installed. Some simple modelling has estimated that for heat demands of 15,000–18,000 kWh per year (small to average heat-demand), around 2500 kWh of electricity would be concurrently generated, enabling financial paybacks of 3→5 years [33,34].

### 3.7. *Other micro-generation options*

Biomass heating and micro-hydro systems are among the other micro-generation options for the UK. They are relatively site specific regarding the required resource, but in appropriate areas they are amongst the most cost-effective technologies under current market conditions, along with ground source heat pumps [30]. A summary comparison of micro-generation technologies is presented in Table 1.

## 4. Policy and legislation in the UK

### 4.1. *Background*

There are numerous UK policy and legislative drivers for energy demand and CO<sub>2</sub> emission reduction. Some of these outline commitments made for energy producers and suppliers, together with incentives for the production of energy using micro-generators. Privatisation of the UK energy-market commenced in the late 1980s with the gas sector, closely followed by similar moves in the electricity, coal and nuclear sectors.

Table 1  
Comparative advantages and disadvantages of different micro-generation technologies

Micro-generation technology	Typical costs	Advantages	Disadvantages
Solar thermal	£2000–£4500	<ul style="list-style-type: none"> <li>• The solar resource is relatively reliable and predictable</li> <li>• Some systems operate renewably (e.g. solar PV powered pump)</li> <li>• Proven/established technology</li> <li>• Visually unobtrusive</li> <li>• Provides hot water all year round (however will not meet demand in winter)</li> </ul>	<ul style="list-style-type: none"> <li>• Some systems require grid electricity supply</li> <li>• Low cost-reduction potential due to established designs</li> <li>• Not currently cost effective</li> </ul>
Solar PV	£6000–£15,000	<ul style="list-style-type: none"> <li>• The solar resource is relatively reliable and predictable</li> <li>• Renewable</li> <li>• Proven in field trials</li> <li>• Visually unobtrusive</li> </ul>	<ul style="list-style-type: none"> <li>• High capital costs</li> <li>• Not currently cost effective</li> </ul>
Micro-wind	£3000–£5000	<ul style="list-style-type: none"> <li>• Can be relatively inexpensive when situated appropriately</li> <li>• Renewable</li> <li>• Matches loosely with the diurnal energy demand</li> </ul>	<ul style="list-style-type: none"> <li>• Very site specific resource</li> <li>• Least predictable intermittent renewable</li> <li>• Lack of available performance information</li> <li>• Some opposition (e.g. due to visual impact)</li> <li>• Not currently cost effective</li> </ul>
Ground-source heat pump	£8000–£12,000	<ul style="list-style-type: none"> <li>• Very reliable – ground temperatures are constant and predictable</li> <li>• Can be cost effective within the current market</li> </ul>	<ul style="list-style-type: none"> <li>• Retrofitting can be problematic (most effective with under-floor heating)</li> <li>• Requires relatively large electricity supply</li> <li>• Land requirement for ground-loops</li> <li>• High capital costs</li> </ul>
Micro-CHP	Approx. £3000	<ul style="list-style-type: none"> <li>• Has the potential to reduce CO<sub>2</sub> emissions related to fossil fuel use through efficiency gains</li> <li>• Some technologies nearing cost-effectiveness</li> </ul>	<ul style="list-style-type: none"> <li>• Currently mostly fossil fuel powered</li> <li>• Has an inflexible heat to power generation ratio, which can be problematic if this does not match the respective demands</li> <li>• Carbon savings appear to be less than originally predicted</li> <li>• Lack of available performance information</li> </ul>
Micro-hydro	–	<ul style="list-style-type: none"> <li>• High energy yields possible</li> <li>• Can be cost effective within the current market</li> </ul>	<ul style="list-style-type: none"> <li>• Application limited by the availability of suitable locations</li> </ul>
Biomass heating	–	<ul style="list-style-type: none"> <li>• Can be cost effective within the current market</li> </ul>	<ul style="list-style-type: none"> <li>• Application limited by the availability of suitable locations</li> </ul>

Oil resources have always been privately controlled. Full privatisation was achieved in 1999 and now all consumers, both domestic and business, are free to choose their gas or electricity supplier.

#### 4.2. Climate Change Levy (2001)

This (CCL) is a tax on the use of energy by industry, commerce, agriculture and the public sector. The CCL applies to all UK non-domestic users of non-renewable energy, including the public, industrial and commercial sectors. However, there are a number of exceptions including good-quality CHP systems; the transport sector; energy supplies used as a feedstock; or fuel used as a raw material, for example coal used to make carbon filters. Under the CCL businesses can enter into Climate Change Agreements with the Government in order to obtain tax reductions in return for reducing carbon-emissions.

#### 4.3. Energy Efficiency Commitment (2001) and Carbon-Emissions Reduction Target (2008)

The Energy Efficiency Commitment (EEC) requires energy suppliers to achieve targets for delivering energy efficiency improvements in households, thus contributing to the UK Government's Climate Change

Programme by cutting GHG emissions. It was set out under the Electricity and Gas (Energy Efficiency Obligations) Statutory Instrument 2001. At least 50% of the target must be met in relation to certain low-income consumers; thereby contributing to the UK Government's Fuel Poverty Strategy [35].

The first and second phases of the EEC ran from April 2002 and April 2005 respectively. The third phase of the EEC (EEC3) has been renamed as the Carbon Emissions Reduction Target 2008–2011 (CERT), and is currently under consultation (ending 15 August 2007). It has the same underlying framework as the EEC, but following the Climate Change and Sustainable Energy Act 2006 it now includes micro-generation and behavioural measures within the scheme. The recent UK Energy White Paper [36] states that in the longer term, from 2012, the UK Government would like to develop the scheme to support a transformation toward a marketplace in which suppliers provide energy services instead of simply supplying units of energy, hence further encouraging energy-conservation.

#### *4.4. Renewables Obligation (RO) (2002)*

This (RO) was introduced by the UK Government in 2002 and requires licensed electricity suppliers to source a proportion of their supply from renewable generators. Renewables Obligation Certificates (ROCs) are issued to generators for each MWh of renewable electricity they generate, which can then be traded on to suppliers to enable them to comply. Suppliers can alternatively pay into a buy-out fund to meet all or part of their obligation [37].

The RO applies to all sizes of generators; however, access to ROCs has been complex for micro-generators as the scheme is aimed primarily at larger renewable-energy schemes [37,38]. The DTI is currently consulting about reform of the RO, and is considering changes to make ROCs access easier for micro-generators, along with proposing to introduce banding, to come into force in 2009 [36] that will offer differentiated levels of support to different renewable-technologies.

The banding of the RO improves the prospects for the development of a range of renewable technologies, as they are competing then within each band, as opposed to with all renewable technologies. However, micro-generators are not separately banded under the new proposals, and hence support for development under this programme is lacking.

#### *4.5. Climate Change and Sustainable Energy Act (2006)*

This aims to promote micro-generation and the use of heat from renewable sources; to make provision for the reduction of greenhouse gases; and to aid in the alleviation of fuel poverty. It requires the Secretary of State to designate one or more national micro-generation targets in the period 1 November 2008 to 21 March 2009. If energy suppliers do not develop a system to buy-back electricity from micro-generators, the Government will intervene.

#### *4.6. Microgeneration Strategy (2006)*

The UK Government's 'Microgeneration Strategy' [39], in combination with the Climate Change and Sustainable Energy Act 2006, aims to promote easier access to ROCs and to promote community energy projects. The strategy outlines opportunities for local authorities to be more proactive in promoting the incorporation of microgeneration through the use of planning policies. In addition it will provide a review of communications activity to assess how to improve information provision [6].

The UK Government is also proposing changes to the planning system from autumn 2007, with the aim of making it easier for homeowners to install many of the available micro-generator technologies [36].

#### *4.7. Low Carbon Buildings Programme (2006)*

The Low Carbon Buildings Programme (LCBP) replaced the DTI Clear Skies and Solar PV grant programmes. Phase 1 funds were available for households and for public, not-for-profit, and commercial organisations. It aimed to encourage applicants to consider energy efficiency measures alongside micro-generation

technologies. Its value was lower than the scheme it replaced and was therefore labelled a “significant step backward” by industry [40].

Demand from homeowners was much higher than the programme allowed for: therefore adjustments were made including a capping of the available monthly funding [41,42]. This did not solve the supply shortfall, and after the allowance for March 2007 ran out within an hour (following rapid exhaustion in previous months), the programme was suspended by the DTI for review amid much controversy.

A second phase now runs until March 2008. Funds are available for the installation of micro-generation technologies by public-sector organisations and charitable bodies (not private households or businesses). Purchase and installation of technologies is limited to a specific shortlist of seven suppliers (“framework suppliers”), and to specific technologies: solar PV; solar thermal; wind; ground source heat pumps; and biomass [42]. The method of framework suppliers has been criticised by some as it excludes a large number of suppliers and installers across the UK.

#### 4.8. *Draft Climate Change Bill (2007)*

The draft Climate Change Bill commits the UK to achieving at least a 60% reduction in CO<sub>2</sub> emissions by 2050, and a 26–32% reduction by 2020, against the 1990 baseline. These targets may be amended in the event of developments in climate science or international law/policy, and the Government will be required to set five-year carbon budgets to place binding limits on aggregate emissions [36].

#### 4.9. *Energy White Paper (2007)*

The Energy White Paper (EWP) [36], published in May 2007, sets out the UK Government’s international and domestic energy-strategies. Underlying these is the view that independently regulated, competitive energy markets are the most cost-effective and efficient way of delivering the UK Government’s objectives of tackling climate change and delivering secure, clean energy at affordable prices. The UK Government’s move towards zero-carbon homes, reduced VAT (5%) for some micro-generation technologies, and the Carbon Trust’s ‘Partnership for Renewables’ (£10 million funds to support public sector organisations wanting to invest in distributed energy) are existing measures intended to support the growth of distributed and micro-generation [36].

The Review of Distributed Generation [44], conducted by the DTI and the Office of Gas and Electricity Markets (OFGEM), informed the EWP [36] and was also published in May 2007. In order to remove barriers and encourage uptake of distributed generation (including micro-generation) the EWP outlines a number of planned measures, including:

- *Improved information services* for consumers, and *guidance on technology options*.
- *More flexible market and licensing arrangements* for distributed, low-carbon electricity supply within the licensed framework, to be implemented by the end of 2008.
- *Clearer export rewards* for smaller generators from the different energy suppliers. Beyond this, the UK Government is engaging with industry with the aim of making it more cost-effective for suppliers to offer export tariffs.
- *Making it easier to connect to and use the distribution network*. Micro-generators under ratings of approximately 4 kW do not generally need to obtain permission to connect to the network, and new wiring regulations will be published in January 2008 that will make it easier to connect micro-generators into existing electrical installations. However, there remain considerable connection difficulties for larger distributed generators – the UK Government states that it intends to address these issues [36].
- *Reducing the carbon impact of heat*. The generation of heat accounts for half of the UK’s total energy consumption by end-use, and 47% of the UK’s total carbon emissions (including emissions from electrical heating). Approximately 75% of this heat is used for space and water heating, primarily in the domestic sector and to a lesser extent in the commercial and public sectors. The remainder is used as process heat in industry. The UK Government is conducting further work into the policy options available to reduce the carbon impact of heat and its use, in order to determine a strategy for heat [36].

## 5. Prospects and barriers

There are a number of advantages to micro-generation that suggest they may have an important role in developing a more sustainable UK energy-system. These include their potential to aid the realisation of carbon reduction targets, and their ability to reduce dependence on fossil fuels and increase energy security. However there are also a number of disadvantages to micro-generation, and there are barriers to entry that can be broadly categorised as technical, economic, and information-related. There will be varying lead-times to the removal of these barriers, but ultimately all must be removed for micro-generation to contribute significantly to energy supply.

Technical barriers include grid-integration, planning permission and licensing. The current electricity network was designed for centralised generation and is optimised for one-way flow, so network changes will be required if distributed generators are to contribute significantly to the energy mix. However, for the short to mid-term, there is some indication that a relatively high penetration of micro-generators could be incorporated into the current electricity-network. Thomson and Infield [43] considered the technical impact of high penetrations of solar PV on low-voltage distribution systems (11 kV, 400 V and 230 V), and indicated that voltage rise is unlikely to constrain PV for many years to come (up to a penetration of around 30%). A more diverse mix of micro-generators would clearly present more varied system characteristics; for example micro-CHP electricity generation profiles are typically determined by heat demand, compared with PV outputs that depend upon the solar resource. Heat generating systems will present other challenges. Alternative future configurations of micro-generators will be discussed further below.

The UK Government has proposed changes to the planning system that will make it easier for homeowners to install micro-generators, which will be a welcome development. Currently licensing and connection issues can be problematic for larger distributed-generators (these issues are under review [36,44]). While this does not directly affect micro-generation, such developments will support the growth of the distributed generation market, which is likely to provide knock-on benefits for domestic micro-generators (such as network alterations and industry learning-by-doing).

Improved information for consumers will benefit the industry. Guidance for micro-generators for obtaining the financial benefits of ROCs is to be published shortly as part of the Low Carbon Buildings Programme [44], which along with easier access to ROCs will improve accessibility for consumers. The recent Review of Distributed Generation [44] for the UK Government outlined a number of measures to stimulate the uptake of distributed generation, including a new certification scheme and a campaign to raise public awareness about CO<sub>2</sub> reductions in the home. However, information relating to the practical energy output of some micro-generators is scarce. Improvements to this situation will benefit consumers, as well as future policy makers aiming to determine the best mechanisms for saving energy and reducing carbon emissions.

Economic barriers are complex and significant. From a whole-system perspective of innovation, it has been argued above that failures exist in current renewables innovation-systems, particularly between the stages of demonstration and pre-commercialisation, and between pre-commercial and commercial development. Contributing to this situation is an apparent lack of coherence and integration in the design of the policy mix; for example, where capital grants were introduced as an 'ad hoc' measure to address the failure of the early Renewables Obligation [45]. The LCBP (the capital grants scheme for micro-generation) has suffered from poor performance since its introduction in April 2006. Upfront costs to consumers are very high (Tables 1 and 2), particularly when compared to the cost of current alternatives (centralised supply).

As an example, the average domestic PV installation in the UK can produce 51% of average annual domestic house electricity demand (as previously discussed above). DTI statistics indicate that the average UK household electricity bill in 2006 was £338 [46]. The average cost of a domestic sized system is £10,400 [23], and the maximum grant available under the recently re-launched LCBP is £2500. Assuming all electricity is consumed onsite (i.e. a direct saving on the bill is made), the payback time would therefore be approximately 48 years. This estimation is purely for illustrative purposes; it does not take buy-back into consideration and the associated financial gains that could be made. Under current UK market conditions Butcher et al. [47] concluded that many micro-generators are uncompetitive, even with the aid of Government grants.

The changes implemented in the CERT (2008–2011), and the national micro-generation targets that can be set in 2008/2009 under the Climate Change and Sustainable Energy Act will encourage energy suppliers to

Table 2  
Number of installed micro-generators and future projects funded by the LCBP (adapted from [9,40])

Micro-generation technology <sup>a</sup>	Total number installed (2005)	Estimated total cost	Avg. cost per install	Projects funded by the LCBP		
				Funds allocated	No. projects	Avg. fund allocated per project (historic)
Solar thermal	78,470	£357,696,065	£4558	£848,067	2122	£400
Solar PV	1301	£20,145,012	£15,484	£3,721,598	510	£7297
Micro-wind	650	£11,137,463	£17,135	£1,730,739	1493	£1159
Ground source heat pumps	546	£5,156,751	£9445	£327,536	274	£1195
Micro-CHP	990	Not known				
Micro-hydro	90	£2,385,084	£26,501	£14,300	4	£3575
Biomass room heaters				£7841	16	£490
Wood fuelled boilers				£168,002	116	£1448

<sup>a</sup> Includes community scale projects.

support the micro-generation industry. Proposals in the recent Review of Distributed Generation [44] include clearer export-rewards from suppliers and new market arrangements for distributed generators, which will benefit the industry as a whole.

While the proposed reforms for the banding of the RO (certificate market) will create more appropriate niche markets for diverse supply, they will not directly benefit the micro-generation industry. Based on the EU research project 'REALISE', Midttun and Gautesen [16] argued that feed-in tariffs and certificate markets can be complementary policy steps in the technology-development cycle. The UK's Marine Renewables Deployment Fund works along similar lines. It offers grants and a feed-in tariff, the latter to create additional revenue on top of the ROC price that is designed to support deployment of wave and tidal technologies. A similar system could also be beneficial for micro-generation.

Over and above all these economic changes, it is apparent that a stable, consistent and long-term framework is required from Governments. This would reduce risk and offer greater incentives for investment in micro-generation and renewables in general. The Draft Climate Change Bill commits the UK to long-term carbon reduction targets, and is therefore an important step in the right direction. Specific targets for renewables (under the RO) and indeed micro-generators (under the Climate Change and Sustainable Energy Act) are also welcome, but the effect of the latter in particular is currently uncertain.

## 6. Potential futures for micro-generation

There are a number of possible future configurations for micro-generator installations, some of which are currently possible and some of which are under consideration in the literature, with varying levels of decentralisation, including:

- (National) grid-tied.
- Micro-grids (including islanding capabilities; see for example [48,49]).
- Off-grid (energy storage; see for example [50,51]).

Grid-tied systems are currently common for electricity micro-generation. Their feasibility is very much affected by the practical changes required to the network but also in a change to the economic framework (buy-back, etc.). Safety is an issue that requires addressing during a move to more decentralised supply, which is perhaps more easily handled within the current centralised system. With a one-way network with few large-scale suppliers it is easy to ensure that no electricity is flowing during maintenance, but with a two way system with many small-scale suppliers it is more difficult to ensure safety. If all supplies are shut off, the possible energy security benefits of decentralised supply would be negated.

Micro-grids are semi-autonomous systems that have the capability of islanding from the main network. This is considered advantageous by many industrial, public and domestic users who wish to have a secure



electricity supply (e.g. hospitals). However, there are technical, safety and legislative issues associated with this which need to be addressed at a national level. An off-grid configuration is a further option for micro-generation, in which case energy storage becomes a key issue. Storage is problematic; currently batteries are the most applicable option, but the efficiency of cost-effective models is low.

The installation and use of smart meters are considered essential by Watson et al. [38]. These can be used to measure half hourly demand, can be linked to display systems that show current and historical consumption data and can also measure imports and exports for those with micro-generators. If micro-generation is to become mainstream this type of meter will allow easier measurements for the supplier and the purchaser. The UK Government is currently running smart meter and real-time display trials, and subject to the results will roll out smart meters over the next ten years. Real-time displays are to be fitted with any new meters fitted from 2008, and between 2008 and 2010 displays will be free-of-charge to any householder on request.

## 7. Concluding remarks

The UK Government acknowledges the potential for distributed energy and micro-generation to aid CO<sub>2</sub> emission reductions and provide reliability of energy supply. It has been shown that, if appropriately installed, micro-generation could provide a significant proportion of energy supply (with demand reduction), for example typical solar PV installations providing 51% of electricity demand [22] and solar thermal systems capable of supplying 33% of hot water requirements [20]. This will lead to reduced carbon-emissions associated with energy supply, reduced dependence on fossil fuels and increased energy-security. There is also a significant demand from the public for engagement with micro-generation, as indicated by the speed at which the LCBP funds were exhausted in early 2007. This suggests good prospects for the market if cost and technical issues can be resolved. Any growth in the micro-generation market is likely to reduce the largely prohibitive upfront costs to consumers.

However, the required financial backing to support and stimulate the market is yet to be forthcoming. The LCBP (capital grants) is currently the major support mechanism for micro-generators, but it is frugal in comparison to the capital costs of some technologies, and has suffered significant administration problems leaving many potential customers unable to obtain grants. It is unlikely that the amount of funding available will stimulate the market sufficiently to lower the capital costs of micro-generators in the near future, and therefore the uptake of distributed energy-systems will remain limited until other mechanisms are in place. In addition, there is a general lack of monitoring and information available about the energy generated by many of the technologies. Although the energy output of many micro-generator types will always be site specific, more information about the output generally obtainable needs to be studied and reported in the open literature.

The many UK Government policy and legislative measures indicate positive intentions, but with varying appropriateness and success, and there remains substantial barriers to a significant rise in the use of micro-generation in the UK.

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